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QUANTITATIVE METHODS FOR PRELIMINARY DESIGN OF WATER QUALITY SURVEILLANCE SYSTEMS

Charles V. Beckers, et al

Raytheon Company

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Quantitative Methods for Preliminary Design of Water Quality Surveillance Systems

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QUANTITATIVE METHODS FOR PRELIMINARY DESIGN OF WATER QUALITY SURVEILLANCE SYSTEMS

By

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Project 16090 HOJ

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27 Abstract

~~This report present~~ the development and successful demonstration of quantitative design methods for preliminary design of water quality surveillance systems. ~~It include~~s a comprehensive set of quantitative design procedures, in handbook form for use within the existing capabilities of governmental water quality agencies. The quantitative methods are intended for use in design of monitoring systems that satisfy an abatement objective. The methods are based on a systems approach, in which the performance of the total surveillance system is evaluated as a whole. A new method for establishing sampling frequency is developed, based on a unique formulation of the sampling design problem. The quantitative preliminary design methods are demonstrated to function satisfactorily on the Wabash River Basin. It is concluded that the methods incorporated in the User Handbook represent an acceptable method for use by governmental water quality agencies under the existing contraints. ~~The report includes 50 references and a User Handbook. The report is submitted in fulfillment of Project Number 16090 HOJ, Contract Number 68-01-0144, under the sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.~~ (EPA abstract)

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ABSTRACT

This report presents the development and successful demonstration of quantitative design methods for preliminary design of water quality surveillance systems. It includes a comprehensive set of quantitative design procedures in handbook form for use within the existing capabilities of governmental water quality agencies. The quantitative methods are intended for use in design of monitoring systems that satisfy an abatement objective. Preliminary design is that portion of the design process that deals solely with the interface between the surveillance system and the monitored system, the river basin. The preliminary design includes specification of station locations, sampling frequencies, and priorities. Incorporation of such practical engineering concerns as cost, reliability and maintainability, and computerization of the procedure are recommended areas for additional development.

The methods are based on a systems approach, in which the performance of the total surveillance system is evaluated as a whole. A new method for establishing sampling frequency is developed, based on a unique formulation of the sampling design problem. The development incorporates a "macroscopic" concept that limits consideration of time and space dimensions to scales compatible with an overview of the river basin. Data availability remains a constraint of the method, even under the "macroscopic" concept; methods are developed for estimation of required design data.

The quantitative preliminary design methods are demonstrated to function satisfactorily on the Wabash River Basin. It is concluded that the methods incorporated in the User Handbook represent an acceptable method for use by governmental water quality agencies under the existing constraints.

This report is submitted in fulfillment of Project Number 16090 HOJ, Contract Number 68-01-0144, under the sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

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SECTION I

SUMMARY AND CONCLUSIONS

Quantitative methods for the preliminary design of water quality surveillance systems are developed and demonstrated in this report. The quantitative methods are organized into a User Handbook (Appendix G).

The quantitative methods are intended for use in preliminary design of surveillance systems which satisfy the abatement objective. Abatement of water pollution places more stringent requirements on a surveillance system than prevention and planning goals [1] . The abatement objective requires that the system detect an acceptable percentage of violations of the federal-state water quality standards.

Preliminary design is that portion of the design process which deals solely with the interface between the surveillance system and the monitored system, the river basin. The surveillance system is characterized by ideal locations of observation and by sampling frequency. A priority is assigned to the observation of each water quality parameter in each stretch of the river. The priority is based on the probability that a violation of the standards will occur for that parameter and on the existence of other observations of that parameter in the vicinity. Sampling frequency is rated according to the expected percentage of violations detected. Such practical engineering concerns as cost, accessibility, reliability, and maintainability are addressed during later design stages, not during preliminary design.

A unique analytical approach to the selection of sampling frequency is taken, based on the requirement that the system detect violations of the water quality standards. The violations are defined in terms of threshold crossings, which eliminates many established techniques of sampling design. The result of the analysis of the time-sampling problem is a new approach to selection of sampling frequency.

The development incorporates a "macroscopic" concept which limits consideration of time and space dimensions to scales compatible with an overview of the entire extent of the basin. This approach permits use of simplified mathematical models in the characterization of the river basin. It also reduces the level of detail required of input data.

However, data availability does remain a constraint. The quantitative methods detailed in the User Handbook (Appendix G) incorporate approximations necessitated by data limitations. Methods are included for estimation of some of the required inputs from more readily available data, such as census information.

The quantitative methods developed are intended for use in a non-computer environment. The emphasis is placed on compilation of tabular, nomographic, and desk calculator approaches. The user, however, is assumed to be familiar with basic engineering mathematics (up to, but not including, calculus). This constraint represents a trade-off between the labor necessary to generate a computer model and that necessary for manual computation.

The quantitative preliminary design methods are demonstrated to function satisfactorily on the Wabash River Basin. Station locations, priorities, and sampling frequencies for the Wabash main stem are derived using the methods on available data for biochemical oxygen demand and dissolved oxygen (BOD-DO). The methods are also applied to Wildcat Creek, a tributary to the Wabash, for both BOD-DO and fluorides. Reasonable results are derived for both the main stem and its tributary.

It is concluded that the quantitative methods incorporated in the User Handbook represent an acceptable method of preliminary design under the existing constraints. The limitations of the method are recognized and recommendations for further development of the quantitative methods are offered in Section II.

SECTION II

RECOMMENDATIONS

The present project has provided a number of opportunities to evaluate the various methods by which water quality surveillance systems are designed. The following recommendations are made on the basis of observations made during the course of the project.

The Environmental Protection Agency (EPA) should begin immediate implementation of the preliminary design procedure described in this report; it appears to constitute a significant improvement over previous methods.

The EPA should provide a mechanism for review and update of the preliminary design procedure as experience is gained in its use, by monitoring applications of the procedure to river basins. The procedure reflects the aggregate of years of scientific research on the behavior of streams, filtered through the judgment of environmental systems analysts. Although the procedure represents the best professional judgment of its authors and has been demonstrated to perform in a reasonable way for one river basin, its general applicability can only be determined by further evaluation and study. Review and update will also permit incorporation of new information in such related areas as the characterization of the effluent dynamics of wastewater treatment plants.

The manual procedures described in this report should be converted to computer techniques. Computerization will benefit the user in two ways. First, the procedures for preliminary design described in this report are laborious. Every attempt has been made to minimize tedious hand computation, through use of tables, graphs, and nomographs. The procedures still require extensive detailed manual calculation, which may limit their usage. Second, by computerizing, the user may take advantage of existing computerized models of river basins. Such models are presently under development by EPA for a number of river basins. Use of these models will provide even better estimates of stream conditions than can be achieved by the manual computations.

The procedure described in this report should be extended to include both the expected total cost of the surveillance system and the anticipated effectiveness of the proposed system in achieving the surveillance goals. The quantitative design procedure is limited to consideration of preliminary design factors. As such, it partially fulfills the intent of the recommendation on which this project is based [2]. Extension to include practical engineering factors would provide a more complete system engineering tool, in line with that recommendation.

The EPA should continue to proceed with their plans to incorporate into STORET more detailed data on such properties as constituents and variability of individual outfalls. The lack of readily available data on outfalls has presented a major obstacle to demonstration. It will present a similary obstacle to application of the methodology under real conditions. Similarly, attention should be given to improvement of available data on distributed pollution sources, such as farmland runoff.

SECTION III

INTRODUCTION

In response to increasing public awareness and concern for the quality of the environment in general, government at all levels is taking steps to protect and enhance the quality of the public waters of the nation. The Federal Water Pollution Control Act of 1956 and its successors, including the Water Quality Act of 1965, are major landmarks in the drive to bring the full cooperative efforts of state and federal governments to bear. The Act of 1956 clearly recognizes the primary responsibilities and rights of the states to control water quality[3]. The federal government assumes a primarily supporting role, including financial aid, research and development, planning, coordination, and technical assistance. The Water Quality Act of 1965 charges the states with the establishment of water quality standards and the development of plans for implementation and enforcement of those standards, under federal guidance.

Water quality surveillance is essential to the success of this initiative toward environmental quality. William T. Sayers has recently pointed out that monitoring of "... the rivers, lakes and coastal waters receiving wastes [is required] to assure attainment and maintenance of desired water quality levels consistent with criteria contained in state-federal water quality standards."[3] He further states the aims of water quality surveillance are "... to assess existing water quality conditions, to determine long-term trends in water quality and to evaluate compliance with state-federal water quality standards."

In order to affect cost-effective monitoring of water quality, the Environmental Protection Agency is supporting a program of technology development aimed at providing standard methods for the further implementation of water quality surveillance systems. This report is one of several recent studies undertaken with EPA support to examine the question of design of water quality data acquisition systems. Two of these studies are reviewed in Section IV to establish the background for the present study.

The objectives of the present study are directed toward the development of quantitative procedures for implementing the qualitative design methods of its predecessors. A detailed discussion of the implications of the study objective is presented in Section V, followed by a description of the approach taken in achieving the objective.

The realization of the study goal required the development of quantitative means for evaluating the priority of observing water quality, for determining preferred locations for sampling, and for measuring the effectiveness of various sampling frequencies. Section VI is devoted to the development of the quantitative procedures, supported by the detailed analyses presented in the Appendices. Appendix G is a User Handbook intended to guide the surveillance-system designer in the application of the quantitative procedure to the subject river basin.

For purposes of confirmation and illustration, the quantitative methods of the User Handbook are applied to portions of the Wabash River Basin in Section VII. A final discussion of the quantitative procedure and its relationship to the overall goals and objectives of water quality surveillance system design is contained in Section VIII.

SECTION IV

DESIGN OF WATER QUALITY SURVEILLANCE SYSTEMS

The present study is an outgrowth and continuation of previous developments in the design of water quality surveillance systems. In particular, the EPA report Design of Water Quality Surveillance Systems [2] provides the systems analytical framework within which the quantitative methods function. Another report, Data Acquisition Systems in Water Quality Management [1], provides a broad analysis of the context in which surveillance systems operate and develops design strategies for various system objectives.

Design of Water Quality Surveillance Systems [2] addresses the question of setting up water quality surveillance systems throughout the country in response to the requirements of the Water Quality Act of 1965. To insure compatibility of individual systems developed by various federal, state, and regional agencies, systems analysis techniques are adapted to the design of the surveillance systems. The analytical techniques are demonstrated in a qualitative manner on three river basins by: 1) reviewing the literature associated with their water quality characteristics; 2) on-site visits to the river-basin areas; 3) comparative review of the interstate water quality standards and plans of implementation; and 4) legal considerations in surveillance program design. The latter investigations disclose some very pertinent limiting aspects of the legal structure as it existed in 1970 and the report details a number of legal problems in the establishment of federal water quality surveillance systems. A number of recommendations are advanced to further development of the systems analytical methods. Among them is one suggesting that ". . . the tasks, functions, and interrelationships as identified in the systems analysis framework should be described in specific quantitative relationships . . ." and that ". . . a user handbook . . . should be developed to describe these techniques and extend their utility." The stated objectives of the present study correspond, in part, to that recommendation. To show the relationship between the prior EPA report and the present one, Figure 7 from Design of Water Quality Surveillance Systems [2] is reproduced here as Figure 1.

The figure summarizes an integrated analysis of all pertinent considerations inherent to the establishment of a water quality surveillance system. It presents a generalized analysis which is compatible with any specific area of geographical interest.

The logic represented in Figure 1 can be divided into two stages of system design development. The first stage comprises those activities that analyze the relationship between the surveillance system and the natural system that is to be monitored. This preliminary design stage deals only with the establishment of water

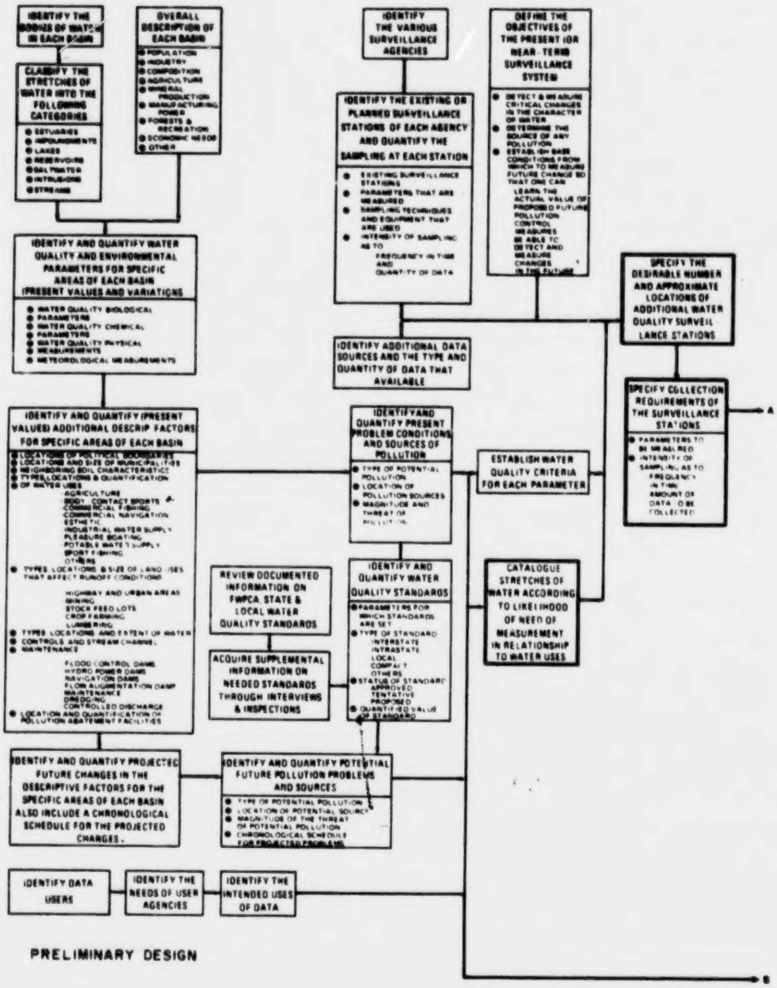
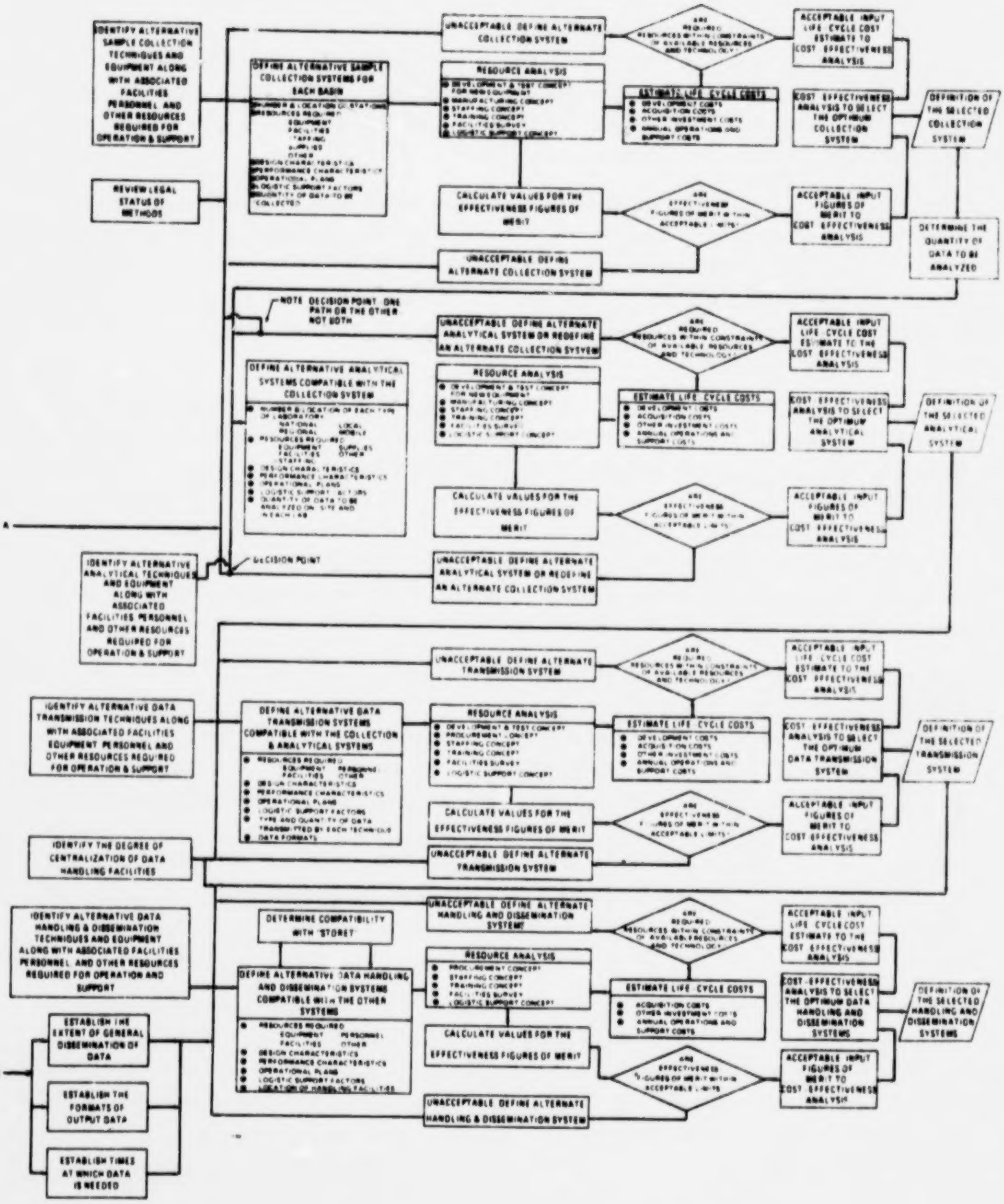

IDENTIFY THE BODIES OF WATER IN EACH BASIN
CLASSIFY THE STRETCHES OF WATER INTO THE FOLLOWING CATEGORIES
● ESTUARIES
● IMPOUNDMENTS
● LAKES
● RESERVOIRS
● SALTWATER
● INTRUSIONS
● STREAMS
OVERALL DESCRIPTION OF EACH BASIN
● POPULATION
● INDUSTRY
● COMPOSITION
● AGRICULTURE
● MINERAL PRODUCTION
● MANUFACTURING POWER
● FORESTS & RECREATION
● ECONOMIC NEEDS
● OTHER
IDENTIFY AND QUANTIFY WATER QUALITY AND ENVIRONMENTAL PARAMETERS FOR SPECIFIC AREAS OF EACH BASIN (PRESENT VALUES AND VARIATIONS
● WATER QUALITY BIOLOGICAL
● PARAMETERS
● WATER QUALITY CHEMICAL
● PARAMETERS
● WATER QUALITY PHYSICAL
● MEASUREMENTS
● METEOROLOGICAL MEASUREMENTS
IDENTIFY THE VARIOUS SURVEILLANCE AGENCIES
IDENTIFY THE EXISTING OR PLANNED SURVEILLANCE STATIONS OF EACH AGENCY AND QUANTIFY THE SAMPLING AT EACH STATION
● EXISTING SURVEILLANCE STATIONS
● PARAMETERS THAT ARE MEASURED
● SAMPLING TECHNIQUES AND EQUIPMENT THAT ARE USED
● INTENSITY OF SAMPLING AS TO
FREQUENCY IN TIME AND
QUANTITY OF DATA
DEFINE THE OBJECTIVES OF THE PRESENT (OR NEAR-TERM SURVEILLANCE SYSTEM
● DETECT & MEASURE CRITICAL CHANGES IN THE CHARACTER OF WATER
● DETERMINE THE SOURCE OF ANY POLLUTION
● ESTABLISH BASE CONDITIONS FROM WHICH TO MEASURE FUTURE CHANGE SO THAT ONE CAN
LEARN THE ACTUAL VALUE OF PROPOSED FUTURE POLLUTION CONTROL MEASURES
BE ABLE TO DETECT AND MEASURE CHANGES IN THE FUTURE
SPECIFY THE DESIRABLE NUMBER AND APPROXIMATE LOCATIONS OF ADDITIONAL WATER QUALITY SURVEILLANCE STATIONS
IDENTIFY ADDITIONAL DATA SOURCES AND THE TYPE AND QUANTITY OF DATA THAT AVAILABLE
SPECIFY COLLECTION REQUIREMENTS OF THE SURVEILLANCE STATIONS
● PARAMETERS TO BE MEASURED
● INTENSITY OF SAMPLING AS TO
FREQUENCY IN TIME
AMOUNT OF DATA TO BE COLLECTED
A
IDENTIFY AND QUANTIFY (PRESENT VALUES) ADDITIONAL DESCRIP FACTORS FOR SPECIFIC AREAS OF EACH BASIN
● LOCATIONS OF POLITICAL BOUNDARIES
● LOCATIONS AND SIZE OF MUNICIPALITIES
● NEIGHBORING SOIL CHARACTERISTICS
● TYPES, LOCATIONS & QUANTIFICATION
● OF WATER USES
AGRICULTURE
BODY CONTACT SPORTS
COMMERCIAL FISHING
COMMERCIAL NAVIGATION
ESTHETIC
INDUSTRIAL WATER SUPPLY
PLEASURE BOATING
POTABLE WATER SUPPLY
SPORT FISHING
OTHERS
● TYPES, LOCATIONS & SIZE OF LAND USES THAT AFFECT RUNOFF CONDITIONS
HIGHWAY AND URBAN AREAS
MINING
STOCK FEED LOTS
CROP FARMING
LUMBERING
● TYPES, LOCATIONS AND EXTENT OF WATER
● CONTROLS AND STREAM CHANNEL
● MAINTENANCE
FLOOD CONTROL DAMS
HYDRO POWER DAMS
NAVIGATION DAMS
FLOW AUGMENTATION DAMS
MAINTENANCE
DREDGING
CONTROLLED DISCHARGE
● LOCATION AND QUANTIFICATION OF POLLUTION ABATEMENT FACILITIES
IDENTIFY AND QUANTIFY PRESENT PROBLEM CONDITIONS AND SOURCES OF POLLUTION
● TYPE OF POTENTIAL POLLUTION
● LOCATION OF POLLUTION SOURCES
● MAGNITUDE AND THREAT OF POLLUTION
ESTABLISH WATER QUALITY CRITERIA FOR EACH PARAMETER
REVIEW DOCUMENTED INFORMATION ON FWPCA, STATE & LOCAL WATER QUALITY STANDARDS
ACQUIRE SUPPLEMENTAL INFORMATION ON NEEDED STANDARDS THROUGH INTERVIEWS & INSPECTIONS
IDENTIFY AND QUANTIFY WATER QUALITY STANDARDS
● PARAMETERS FOR WHICH STANDARDS ARE SET
● TYPE OF STANDARD
INTERSTATE
INTRASTATE
LOCAL
COMPACT
OTHERS
● STATUS OF STANDARD
APPROVED
TENTATIVE
PROPOSED
● QUANTIFIED VALUE OF STANDARD
CATALOGUE STRETCHES OF WATER ACCORDING TO LIKELIHOOD OF NEED OF MEASUREMENT IN RELATIONSHIP TO WATER USES
IDENTIFY AND QUANTIFY PROJECTED FUTURE CHANGES IN THE DESCRIPTIVE FACTORS FOR THE SPECIFIC AREAS OF EACH BASIN ALSO INCLUDE A CHRONOLOGICAL SCHEDULE FOR THE PROJECTED CHANGES.
IDENTIFY AND QUANTIFY POTENTIAL FUTURE POLLUTION PROBLEMS AND SOURCES
● TYPE OF POTENTIAL POLLUTION
● LOCATION OF POTENTIAL SOURCE
● MAGNITUDE OF THE THREAT OF POTENTIAL POLLUTION
● CHRONOLOGICAL SCHEDULE FOR PROJECTED PROBLEMS
IDENTIFY DATA USERS
IDENTIFY THE NEEDS OF USER AGENCIES
IDENTIFY THE INTENDED USES OF DATA
PRELIMINARY DESIGN
B

Figure 1. General Systems Analysis Framework (Sheet 1 of 2)


IDENTIFY ALTERNATIVE SAMPLE COLLECTION TECHNIQUES AND EQUIPMENT ALONG WITH ASSOCIATED FACILITIES PERSONNEL AND OTHER RESOURCES REQUIRED FOR OPERATION & SUPPORT
REVIEW LEGAL STATUS OF METHODS
DEFINE ALTERNATIVE SAMPLE COLLECTION SYSTEMS FOR EACH BASIN
NUMBER & LOCATION OF STATIONS
RESOURCES REQUIRED
EQUIPMENT
FACILITIES
STAFFING
SUPPLIES
OTHER
DESIGN CHARACTERISTICS
PERFORMANCE CHARACTERISTICS
OPERATIONAL PLANS
LOGISTIC SUPPORT FACTORS
QUANTITY OF DATA TO BE COLLECTED
UNACCEPTABLE DEFINE ALTERNATE COLLECTION SYSTEM
RESOURCE ANALYSIS
DEVELOPMENT & TEST CONCEPT FOR NEW EQUIPMENT
MANUFACTURING CONCEPT
STAFFING CONCEPT
TRAINING CONCEPT
FACILITIES SURVEY
LOGISTIC SUPPORT CONCEPT
ARE REQUIRED RESOURCES WITHIN CONSTRAINTS OF AVAILABLE RESOURCES AND TECHNOLOGY?
ESTIMATE LIFE CYCLE COSTS
DEVELOPMENT COSTS
ACQUISITION COSTS
OTHER INVESTMENT COSTS
ANNUAL OPERATIONS AND SUPPORT COSTS
ACCEPTABLE INPUT LIFE CYCLE COST ESTIMATE TO COST EFFECTIVENESS ANALYSIS
COST EFFECTIVENESS ANALYSIS TO SELECT THE OPTIMUM COLLECTION SYSTEM
DEFINITION OF THE SELECTED COLLECTION SYSTEM
CALCULATE VALUES FOR THE EFFECTIVENESS FIGURES OF MERIT
ARE EFFECTIVENESS FIGURES OF MERIT WITHIN ACCEPTABLE LIMITS?
ACCEPTABLE INPUT FIGURES OF MERIT TO COST EFFECTIVENESS ANALYSIS
DETERMINE THE QUANTITY OF DATA TO BE ANALYZED
UNACCEPTABLE DEFINE ALTERNATE COLLECTION SYSTEM
NOTE DECISION POINT ONE PATH OR THE OTHER NOT BOTH
UNACCEPTABLE DEFINE ALTERNATE ANALYTICAL SYSTEM OR REDEFINE AN ALTERNATE COLLECTION SYSVEM
DEFINE ALTERNATIVE ANALYTICAL SYSTEMS COMPATIBLE WITH THE COLLECTION SYSTEM
NUMBER & LOCATION OF EACH TYPE OF LABORATORY
NATIONAL
LOCAL
REGIONAL
MOBILE
RESOURCES REQUIRED
EQUIPMENT
SUPPLIES
FACILITIES
OTHER
STAFFING
DESIGN CHARACTERISTICS
PERFORMANCE CHARACTERISTICS
OPERATIONAL PLANS
LOGISTIC SUPPORT FACTORS
QUANTITY OF DATA TO BE ANALYZED ON SITE AND IN EACH LAB
RESOURCE ANALYSIS
DEVELOPMENT & TEST CONCEPT FOR NEW EQUIPMENT
MANUFACTURING CONCEPT
STAFFING CONCEPT
TRAINING CONCEPT
FACILITIES SURVEY
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ARE EFFECTIVENESS FIGURES OF MERIT WITHIN ACCEPTABLE LIMITS?
ACCEPTABLE INPUT FIGURES OF MERIT TO COST EFFECTIVENESS ANALYSIS
IDENTIFY ALTERNATIVE ANALYTICAL TECHNIQUES AND EQUIPMENT ALONG WITH ASSOCIATED FACILITIES PERSONNEL AND OTHER RESOURCES REQUIRED FOR OPERATION & SUPPORT
DECISION POINT
UNACCEPTABLE DEFINE ALTERNATE ANALYTICAL SYSTEM OR REDEFINE AN ALTERNATE COLLECTION SYSTEM
UNACCEPTABLE DEFINE ALTERNATE TRANSMISSION SYSTEM
ARE REQUIRED RESOURCES WITHIN CONSTRAINTS OF AVAILABLE RESOURCES AND TECHNOLOGY?
ACCEPTABLE INPUT LIFE CYCLE COST ESTIMATE TO THE COST EFFECTIVENESS ANALYSIS
IDENTIFY ALTERNATIVE DATA TRANSMISSION TECHNIQUES ALONG WITH ASSOCIATED FACILITIES EQUIPMENT PERSONNEL AND OTHER RESOURCES REQUIRED FOR OPERATION & SUPPORT
DEFINE ALTERNATIVE DATA TRANSMISSION SYSTEMS COMPATIBLE WITH THE COLLECTION & ANALYTICAL SYSTEMS
RESOURCES REQUIRED
EQUIPMENT
PERSONNEL
FACILITIES
OTHER
DESIGN CHARACTERISTICS
PERFORMANCE CHARACTERISTICS
OPERATIONAL PLANS
LOGISTIC SUPPORT FACTORS
TYPE AND QUANTITY OF DATA TRANSMITTED BY EACH TECHNIQUE
DATA FORMATS
RESOURCE ANALYSIS
DEVELOPMENT & TEST CONCEPT
PROCUREMENT CONCEPT
STAFFING CONCEPT
TRAINING CONCEPT
FACILITIES SURVEY
LOGISTIC SUPPORT CONCEPT
ESTIMATE LIFE CYCLE COSTS
DEVELOPMENT COSTS
ACQUISITION COSTS
OTHER INVESTMENT COSTS
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IDENTIFY THE DEGREE OF CENTRALIZATION OF DATA HANDLING FACILITIES
UNACCEPTABLE DEFINE ALTERNATE TRANSMISSION SYSTEM
UNACCEPTABLE DEFINE ALTERNATE HANDLING AND DISSEMINATION SYSTEMS
IDENTIFY ALTERNATIVE DATA HANDLING & DISSEMINATION TECHNIQUES AND EQUIPMENT ALONG WITH ASSOCIATED FACILITIES PERSONNEL AND OTHER RESOURCES REQUIRED FOR OPERATION AND SUPPORT
DETERMINE COMPATIBILITY WITH "STORET"
ARE REQUIRED RESOURCES WITHIN CONSTRAINTS OF AVAILABLE RESOURCES AND TECHNOLOGY?
ACCEPTABLE INPUT LIFE CYCLE COST ESTIMATE TO THE COST EFFECTIVENESS ANALYSIS
RESOURCE ANALYSIS
PROCUREMENT CONCEPT
STAFFING CONCEPT
TRAINING CONCEPT
FACILITIES SURVEY
LOGISTIC SUPPORT CONCEPT
DEFINE ALTERNATIVE DATA HANDLING AND DISSEMINATION SYSTEMS COMPATIBLE WITH THE OTHER SYSTEMS
RESOURCES REQUIRED
EQUIPMENT
PERSONNEL
FACILITIES
OTHER
DESIGN CHARACTERISTICS
PERFORMANCE CHARACTERISTICS
OPERATIONAL PLANS
LOGISTIC SUPPORT FACTORS
LOCATION OF HANDLING FACILITIES
ESTIMATE LIFE CYCLE COSTS
ACQUISITION COSTS
OTHER INVESTMENT COSTS
ANNUAL OPERATIONS AND SUPPORT COSTS
COST-EFFECTIVENESS ANALYSIS TO SELECT THE OPTIMUM DATA HANDLING AND DISSEMINATION SYSTEMS
DEFINITION OF THE SELECTED HANDLING AND DISSEMINATION SYSTEMS
B
ESTABLISH THE EXTENT OF GENERAL DISSEMINATION OF DATA
ESTABLISH THE FORMATS OF OUTPUT DATA
ESTABLISH TIMES AT WHICH DATA IS NEEDED
CALCULATE VALUES FOR THE EFFECTIVENESS FIGURES OF MERIT
ARE EFFECTIVENESS FIGURES OF MERIT WITHIN ACCEPTABLE LIMITS
ACCEPTABLE INPUT FIGURES OF MERIT TO COST EFFECTIVENESS ANALYSIS
UNACCEPTABLE DEFINE ALTERNATE HANDLING & DISSEMINATION SYSTEM

Figure 1. General Systems Analysis Framework (Sheet 2 of 2)

quality sampling on the basis of scientific and social considerations. The second, or final, design stage is composed of those activities which are aimed at the selection of the "best" realization of the preliminary design. The practical considerations of engineering, legal constraints, cost, reliability, and existing surveillance are used, during the final design stage, to select a preferred implementation of the surveillance system.

This report deals with the preliminary design stage of surveillance system design. The quantitative methods developed and demonstrated in this document deal with the question of how best to monitor a river basin from the perspective of enforcement of water quality standards. Those activities related specifically to preliminary design of water quality surveillance systems are shown within the broken line in Figure 1.

The major outputs from the preliminary design stage are identified with three blocks in Figure 1. One is a catalog of stretches of water according to the likelihood of need to monitor the segment. Need to monitor is determined in relationship to the existing or proposed water uses. Another is the specification of locations for the observation of water quality. The third is the specification of intensity of observation at the surveillance stations. Determination of each of the three preliminary design outputs is based on a number of considerations, as diagramed in the general systems analysis framework.

The natural system to be monitored must be carefully described. Factors included in the description are geography, demography, and historical water quality. A number of elements must be considered in each factor. Geography includes not only the physical description of the river itself, but also such elements as the location of cities, towns, major industries, and farmlands bordering the streams. Population is a major indicator of potential for water quality degradation. Methods for estimation of impact based on demographic data are available [4]. Historical water quality provides information for evaluation of the existing situation in the basin and for prediction of water quality variability to be anticipated over the life of the surveillance system.

While the general systems analysis framework calls for analysis of desired water uses, the procedures developed in this report do not specifically require study of that aspect. The water quality standards of most states are based on an established pattern of water use and reflect the state's determination of its water quality needs (see Appendix B and Section VI).

Similarly, the procedures do not specifically require the identification of existing surveillance networks. They do provide a mechanism for incorporation of such data in the development of the preliminary design, should the user choose to consider the additional factor.

In summary, the contents of this report provide detailed quantitative procedures for accomplishment of the first stage of the generalized design framework established in Design of Water Quality Surveillance Systems [2].

The design and operation of surveillance systems is carried on in the context of water quality management. The EPA report Data Acquisition Systems in Water Quality Management [1] identifies two general objectives for surveillance systems in that context: prevention and abatement. The information requirements of the objectives are delineated in general terms and a procedure is developed for designing a state water quality surveillance program. The program design procedure has two major aspects: 1) the determination of the state agency's strategy, and 2) characterization of the streams in the state so that sampling locations and frequencies may be determined.

Again, the quantitative preliminary design methods developed in this report can work within the state-wide program design procedure to provide numerical priorities, preferred sampling locations, and a quantitative measure of sampling frequency effectiveness for each river basin. The quantitative procedure is intended for use in design of systems with the abatement goal, but it incorporates the recommended prevention approach for stretches of river having low need for monitoring. In general, systems designed to the abatement goal will satisfy the data needs of prevention strategies as well [1].

The methods for selection of state agency strategy [1] may be employed to determine applicability of the quantitative preliminary design methods to the needs of the state agency. An emphasis on abatement goals in the agency's water quality management program would indicate selection of the methods developed in this report for use in system design.

A further discussion of the EPA report Data Acquisition Systems in Water Quality Management [1] is presented in Section VIII of this report, where a specific comparison of the methods developed in the two reports is presented.

SECTION V

STUDY OBJECTIVE AND APPROACH

While the study reported in this document is an outgrowth and extension of the previous developments described in Section IV, the scope of the present project is narrower than that of its predecessors. In this section, the objective of the study is presented and discussed. The study objective is followed by a description of the study plan, or approach, taken in achieving the study objective.

Study Objective

The objective of the study was the development and demonstration of a quantitative procedure for specifying the location, frequency of sampling, and priority of a system of stations for the observation of river basin water quality to effectively enforce compliance with water quality standards.

The system design procedure was to include determination of the location of all necessary surveillance stations within a river basin and the frequency of measurement of each water quality parameter to be measured at each station. The procedure was to be capable of assigning a quantitative priority indicator to each station and sampling schedule evolving from the ideal design, to aid program planning and budgeting activities. The design procedure was to be capable of operating on river basins of various sizes, and of utilizing the STORET system and other available data bases. The procedure was to be based on water quality enforcement program needs and the physical characteristics of river basins (hydrology, pollutant sources, past water quality, etc.). Finally, the procedure was to be demonstrated on a river basin of EPA's choice, having extensive data of the type required for the design procedure.

The scope of the study was, thus, limited to the preliminary design stage of surveillance system design. Consideration of cost, legal status, reliability, and other final design factors was specifically excluded. Also specifically excluded from consideration were estuarine conditions requiring multidimensional analysis.

To improve the general applicability of the procedures, they were to be presented in a "handbook" form and to be limited to techniques which might be performed without resort to the use of an automatic digital computer. This form of presentation anticipated the use of the procedure in a wide variety of organizations and regions, with varying scientific and engineering resources, and with unique local problems. Procedures developed under these constraints would be amenable to later computerization, should that be deemed advisable.

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Study Approach

A number of potential technical approaches exist for the quantitative design of a water quality surveillance system. Among the candidates are techniques based on spectral analysis, quasi-deterministic analysis of water quality, and statistical analysis of random processes.

The study approach was aimed at the selection of the proper mix of technologies, based on a thorough analysis of the preliminary design problem. While some techniques, such as spectral analysis, could be eliminated rapidly based on the constraints of available data or user capability, the correct utilization of others needed detailed study.

Thus, the study approach called, first, for the analysis of the context in which the procedures would be used. The analysis included an extensive examination of STORET, and other data bases, from the viewpoint of sampling methodology. The nature of the data contained in such systems was expected to form a significant constraint on the preliminary design procedure. For example, the general frequency of sampling found in STORET was known to be low enough to effectively eliminate spectral analysis techniques. The analysis also included a review of the federal-state water quality standards. As a central element in the enforcement of water quality regulations, the form of the standards would shape the quantitative preliminary design methods. Of particular interest was the extent to which the standards had been quantified.

Having thus established the operational context of the quantitative procedures, the next step was the theoretical development of the methods for establishing priority, location, and sampling frequency. The objectives of the study were interpreted on the basis of the preceding EPA report [2] . Priority was equated with the need to monitor a particular stretch of river. Location of sampling stations was based on maximum priority conditions, while sampling frequency was examined from the viewpoint of effectiveness.

The theoretical methods were then used to generate a handbook procedure for application to actual design situations. The thrust was to provide a step-by-step guide for use of the procedure. Particular attention was paid to means of estimating design quantities from the typically limited data available.

Selection of the demonstration case and application of the quantitative preliminary design procedure followed its development. An important aspect of the demonstration activity was the feedback provided to update the quantitative procedure. Experience with application of the procedure could be expected to disclose weaknesses and suggest improvements.

In the next section, the results of the quantitative methods development are presented. These are followed, in Section VII, by a description of the demonstration of those methods.

SECTION VI

DEVELOPMENT OF QUANTITATIVE METHODS

This section of the report describes the supporting technical material, assumptions and decisions which resulted in the quantitative procedure detailed in the User Handbook (Appendix G). Extensive use is made of accepted mathematical models of stream processes, without detailed discussion or derivation of the models. References are given where appropriate in the text. The reader may wish to familiarize himself with Simplified Mathematical Modeling of Water Quality [4] before reading the section.

The section begins with a summary of the quantitative methods and the results to be obtained from application to surveillance system design. Next some of the fundamental concepts of system design are presented. The quantitative methods for preliminary design are then developed around those concepts, beginning with the priority of monitoring. Location of stations and the time sampling design methods follow in that order. Additional concepts are introduced as needed in the presentation.

The major portion of the development is given in terms of one parameter set, biochemical oxygen demand-dissolved oxygen (BOD-DO). The limitation is made for purposes of clarity. The BOD-DO case is selected for several reasons. It is of general interest to the user community; it is one of the most commonly cited parameters in the federal-state standards (Appendix B); and it is representative of the general mathematical class of coupled parameters.

Summary of Quantitative Methods for Preliminary Design

Application of the quantitative preliminary design procedure contained in the User Handbook (Appendix G) results in the computation of three sets of quantitative design factors. One is a set of numerical priorities rating the need to monitor each stretch of the river for each water quality parameter of interest to the designer. The second set specifies the preferred location for sampling each of these parameters in each stretch of the river. The third gives a quantitiative measure of the effectiveness of each candidate sampling rate, for each

To achieve these results, the procedure gives step-by-step directions, beginning with the gathering of the data necessary to provide an adequate characterization of the river basin to be monitored. The river basin is then divided into stretches of water (segments) based primarily on the identification of major effluent sources (frequently groupings of smaller sources) and their regions of

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dominant influence. The expected behavior of each parameter of interest is then characterized for each segment. Using this information, the preferred station locations are identified, and the need to monitor each segment for each parameter is computed. The final step is calculation of the set of values describing the effectiveness of alternate sample schedules in detecting water quality standards violations. For very high quality segments, a method for computing sampling frequency for long-term trend analysis is substituted.

Two features of the procedure may be noted. First, it incorporates a means of re-assessing segment priority as sampling stations are established in the basin. Second, while the procedure is intended primarily for design of surveillance systems to detect violations of standards, it tends to identify high quality segments as well and includes methods for establishment of surveillance requirements for long-term trend analysis.

Concept of System Duration

Throughout the development of the quantitative preliminary design method, an implicit concept of the anticipated system duration is used. System duration is defined as that time over which the water quality surveillance system will maintain a fixed configuration of spatial and temporal sampling. It is the time over which average effectiveness of the system would be computed in a cost-effectiveness analysis.

Thus, all the system design factors are average factors over the system duration. The need to monitor a stretch of river is essentially the average need to monitor for the planned system duration. Similarly, the measure of time sampling effectiveness is essentially the average effectiveness for the total span of the planned period of system operation.

For example, it should be clear that a finite, possibly large, difference may exist between the time sampling effectiveness as estimated for an annual cycle and the actual system performance based solely on the low-flow period. The long sampling interval appropriate to provide an acceptable level of effectiveness throughout the year may tend to miss a large percentage of those violations which occur during the low-flow period. A sampling interval aimed at maximizing the measure of effectiveness during the low-flow period will, of course, yield an acceptable level of effectiveness throughout a year period as well, but the cost of operating such a system could be prohibitive.

An essential input to the preliminary design process is, therefore, the planned or intended system duration. If costs and other factors are such that the system may be changed during the annual cycle, the methods developed in this report permit design for those system durations, as well as longer ones. Because choice of the planned system duration depends on factors specifically excluded from consideration in this study (such as cost), system duration must be treated as an input factor, based on a decision external to the quantitative preliminary design process.

In the design methods detailed in the User Handbook (Appendix G), selection of appropriate estimators for various system design factors is based on the chosen value for planned system duration.

Characterization of the Natural System

The initial step in the preliminary design of a water quality surveillance system is the characterization of the processes to be monitored.

The objective of characterization is to sufficiently restrict the range of new information necessary from the surveillance system, so that it may be specifically designed to respond only in the range of interest. If nothing were known of the natural system to be monitored, it would be necessary to establish a finely spaced, intensely sampled surveillance system to assure a high probability of observing the property or event of interest. As the level of initial information on the monitored system is improved, the surveillance system may be more carefully designed to monitor only that which is of interest. This line of reasoning leads to the interesting paradox that design of the true optimum surveillance system requires perfect, advance knowledge of the behavior of the monitored system, which obviates the need for surveillance.

Since such perfect advance knowledge is not found in practical design situations, it is desirable to strive for the best available characterization within planning budgets, in order to improve the expected surveillance-system performance. In order to achieve this goal in preliminary system design, it is necessary to rely on generalized models of stream processes, which are fit to the subject river basin through use of existing historical data.

The level of detail achievable in the characterization of river basins through use of mathematical models for planning purposes is limited primarily by the availability of data and by the effort expended in calibrating and exercising the model. Knowledge of the anticipated data availability and intended level of preliminary design effort can be used to select appropriately detailed mathematical models for use in surveillance system design.

The mathematical models used for characterization of river basins in preliminary design of surveillance systems have been selected on the basis of their general acceptance, their relative simplicity, their compatibility with available water quality data, and their compatibility with the available data base. A review of some aspects of the models concludes the discussion of characterization.

The "Macroscopic" Concept

In the development of the quantitative preliminary design methodology, "macroscopic" time and space scales have been employed. An initial understanding of the "macroscopic" concept may be gained by imagining the appearance of a river basin as seen from high altitude (a manned earth satellite, for example). Major cities reduce to points and the river network itself assumes a one-dimensional appearance, a line connecting the city-points.

The objective in assuming a "macroscopic" viewpoint is the development of a model of the stream system which is compatible with the level at which the surveillance system will operate. The surveillance system will be employed to ascertain the status of the river basin as a whole and the overall water quality of stretches of river, in particular. It is not intended that the surveillance system be used to determine the precise cause and extent of water quality degradation. Definition of detailed local problems is not a monitoring function; it requires, in general, the implementation of a special-purpose, intensive water quality survey of a stretch of water. Furthermore, it is anticipated that the operational constraints, such as personnel, equipment and financial support, would restrict implementation of a high-intensity sampling network, even if one were desired.

In practice, the "macroscopic" concept restricts the spatial scales of interest. The stream is treated as a one-dimensional flow, with depth and width entering only as they influence the values of coefficients and other input variables, such as velocity. Outfalls located in "close" proximity to each other are grouped and treated as a single source, based on a quantitative measure of closeness. Cities, in particular, are treated as point sources of effluents.

Commensurate with the space scale, the time scale is restricted to very slow variations, those taking place over days. Computation of spatial factors is based on time-averaged inputs. Specification of sampling rates is constrained to integer days and the inputs to computation are comparably scaled.

In addition to the conceptual requirements, there are practical reasons for the use of the "macroscopic" concept. Refinement of the level of system-design detail requires a comparable refinement of the data on which the design is based. The data required by the "macroscopic" approach is generally available, although gaps have been noted. The quantity and quality of data useful to more fine-scaled planning is severely limited.

Review of Data Base

The data base necessary for characterization of the natural system may be divided into three categories:

1) stream data
2) discrete pollution source data
3) distributed pollution source data.

Stream data is the aggregate of historical records on the quality of the water in the stream bed. Some 700 plus individual descriptors of the stream water quality (water quality parameters) have been identified, including stream flow, other physical properties, and chemical and biological properties [5] .

Discrete pollution source data refers to data on the nature of effluents entering the stream from discrete outfall sources. Distributed pollution source data refers to information on such pollution sources as mine drainage, benthic demand, natural sources, and farm and feedlot runoff. These occur along a length of stream and are not readily identified with a single location.

A survey of the stream data expected to be available to the user of the quantitative design procedure was conducted. The detailed results are presented in Appendix A. In summary, water quality data may be expected to be generally available, but the spatial and temporal intensity tends to be low. Thus, it is necessary to the quantitative design procedure that mathematical models of stream processes be used to extrapolate and interpolate these data for stream characterization. Specific data sources include STORET, U.S. Geological Survey stream flow records and state agency files; a comprehensive listing is given in the User Handbook (Appendix G).

Detailed data on discrete waste outfalls is not generally available, and in many cases even precise location of outfalls is not known [1] . The level of information on municipal wastewater treatment plant outfalls is better, typically, than that on industrial sources, due to the impact of financial assistance and regulation programs on wastewater treatment plants. The cataloguing of industrial outfalls under the Refuse Act Permit Program may be expected to bring improvement in this category.

However, detailed data on the composition and variability of discrete source effluents, both municipal and industrial, is expected to remain a problem. For example, existing data on municipal treatment plants is frequently limited to three days per week. Methods for estimating the necessary inputs on these sources have, therefore, been incorporated into the User Handbook (Appendix G), for use when good information is lacking. These methods include a means to estimate wastewater treatment plant impact based on population and type of treatment [4] . Use of standard textbook values for typical effluents based on Standard Industrial Codes [6, 7, 8] , and estimates based on the professional experience of the project staff and consultants (for example, use of 2 mg/1 as the typical DO of wastewater treatment plant effluents). These techniques are necessarily gross estimates; the availability of better methods remains an area for improvement in the quantitative design procedure.

Improvement in the status of distributed pollution source data is not as easily foreseen as improvement in discrete pollution source data, although it is as necessary. While discrete sources may be readily identified and analyzed, distributed sources are less tractable. It cannot be expected that detailed descriptions of specific distributed sources in every reach of a river basin will become commonly available. An alternative is research aimed at describing the typical characteristics of such sources. Even this type of data is not presently available for the majority of water quality parameters mentioned in the federal-state standards (Appendix B). Appropriate guidelines have been incorporated in the User Handbook (Appendix G), based on the investigation of the project team and available reference material [9, 10, 11]. In most cases, the guidelines call for analysis of the stream quality in relatively remote stretches of river to ascertain the distributed source loads to be assumed throughout the basin. In some cases, such as BOD-DO, tables are provided based on source literature [4]. (Another alternative, of course, is the use of more complex mathematical models than may be conveniently employed in a non-computer setting. That alternative is not available in the context of this study.)

Mathematical Modeling for Stream Characterization

Because of the limited availability of stream data, it is necessary to turn to generalized models of stream water quality for purposes of stream characterization. The most useful models for this purpose are those which describe the desired water quality parameter in terms of available data through use of an analytical (mathematical) relationship.

The mathematical models selected for use in the quantitative preliminary design method are those typified by Simplified Mathematical Modeling of Water Quality [4]. They were chosen on the basis of their wide-spread acceptance and long usage, compatibility with the "macroscopic" concept, and minimal demands on input information [11, 12, 13, 14, 15, 16].

The mathematical models may be described as one-dimensional, steady-state models. That is, only one linear stream dimension is considered, longitudinal distance along the stream bed, and it is assumed that changes in the system take place at a rate which does not significantly affect the description of the system. Properties of the stream (such as width and depth) and of the water quality parameters enter the equations in the form of coefficients. Effluents are assumed to mix with the stream immediately at the point of discharge.

It should be noted that use of one-dimensional models limits the consideration of reservoirs and lakes. While this does not constitute a severe limitation, care must be used in application of the models. In particular, it is necessary to re-initialize the models downstream of such bodies, through use of either stream data or assumed conditions.

For the purposes of quantitative preliminary design, the steady-state conditions correspond to the mean conditions in the stream over the system duration. The validity of this approach is confirmed in Stochastic Modeling for Water Quality Management [17]. (See also [18].) The bars over some of the symbols indicate use of the mean value over system duration.

The mathematical models used in Appendices D, F, and G for synthesis of the quantitative procedure may be classified as either:

1) Conservative
2) Non-conservative, non-coupled
3) Non-conservative, coupled.

Conservative mathematical models describe processes in which the property does not decay with time; the intensity (concentration) of the parameter is reduced only by dilution. Such non-interacting parameters as salinity, total dissolved solids, and the total nitrogen are described with conservative models [4]. Figure 2 diagrams the spatial characteristics of a conservative parameter, with three sources entering the stream. One of the sources indicated is a tributary stream. This is done to illustrate the broad meaning of the term "source" when used in mathematical modeling. The only factors affecting the concentration of the conservative parameter in the stream are the flow in the stream ($\bar{Q}$) and the concentration of the sources ($\bar{C}_s$), including the initial concentration in the stream ($\bar{C}(0)$). The flow in the stream at any point may be written as

$$\bar{Q}(x) = \bar{Q}(0) + \sum_i \bar{Q}_s(x_i), \quad x_i \le x \tag{1}$$

where $\bar{Q}_s$ = the mean flow contributed by the source at x_i. The concentration in the stream at any point is, then:

$$\bar{C}(x) = \frac{\bar{C}(0)\,\bar{Q}(0) + \sum_i \bar{C}_s(x_i)\,\bar{Q}_s(x_i)}{\bar{Q}(x)}, \quad x_i \le x \tag{2}$$

Non-conservative mathematical models are used to characterize water quality parameters which change concentration with both time and dilution. In these cases, first-order kinetics are assumed and a decay rate coefficient assigned for each parameter. The decay coefficient is a function of the parameter and

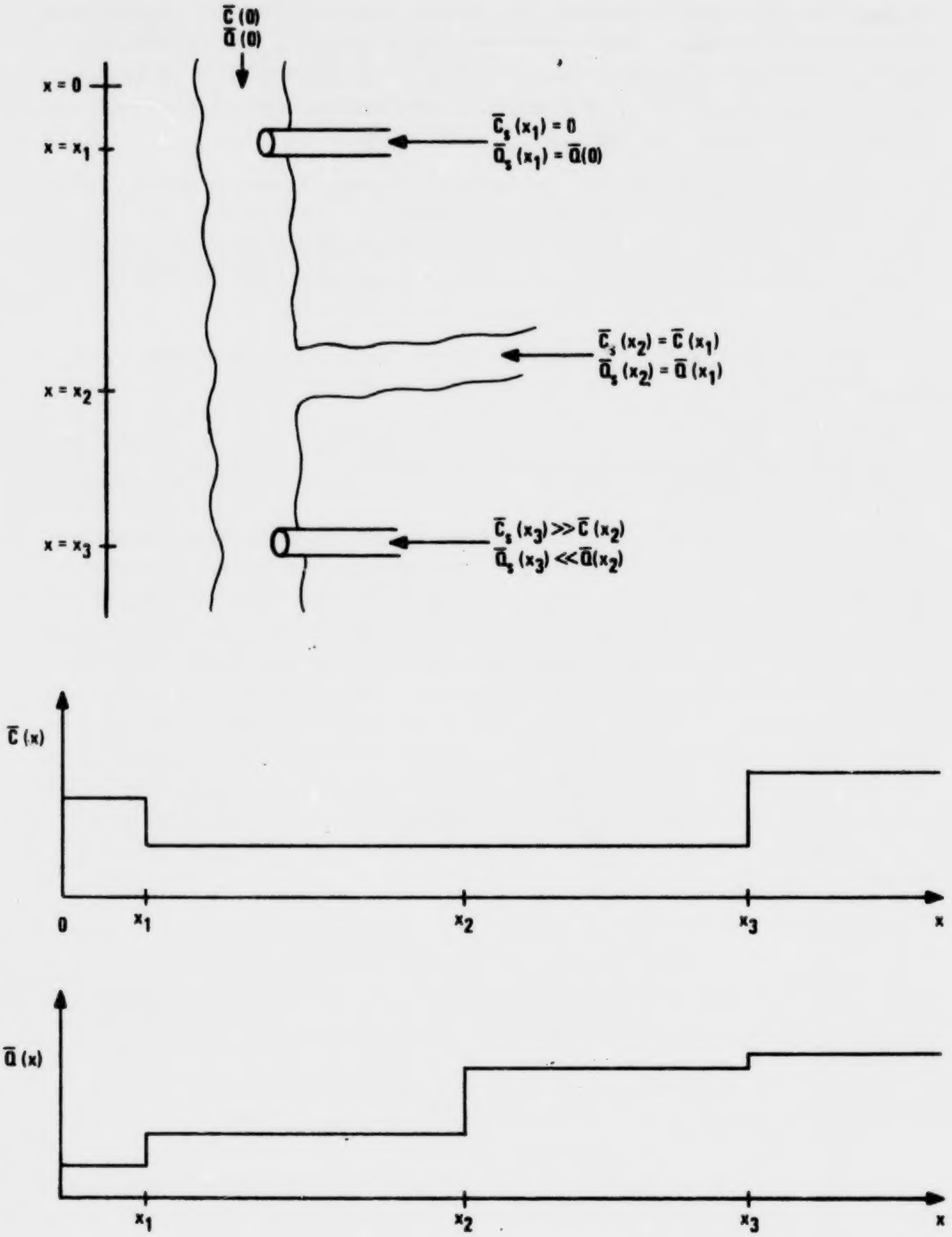

$\bar{C}(0)$
$\bar{Q}(0)$
$x = 0$
$x = x_1$
$x = x_2$
$x = x_3$
$\bar{C}_s(x_1) = 0$
$\bar{Q}_s(x_1) = \bar{Q}(0)$
$\bar{C}_s(x_2) = \bar{C}(x_1)$
$\bar{Q}_s(x_2) = \bar{Q}(x_1)$
$\bar{C}_s(x_3) \gg \bar{C}(x_2)$
$\bar{Q}_s(x_3) \ll \bar{Q}(x_2)$
$\bar{C}(x)$
0
x_1
x_2
x_3
x
$\bar{Q}(x)$
x_1
x_2
x_3
x

Figure 2. Illustration of Stream Characterization For Conservative Parameters

the physical characteristics of the stream. Since these factors vary along the length of the stream, the decay coefficients are (strictly) functions of location on the stream.

The non-conservative models can be divided into two classes, non-coupled and coupled. The non-coupled models describe parameters which are modified solely by their own decay (and by dilution), such as temperature and BOD.

The coupled models are applied to those parameters which are influenced by the behavior of other parameters. For example, dissolved oxygen is affected not only by exchange with the atmosphere but also by the oxygen uptake of BOD.

Figure 3 illustrates the case of a non-conservative, non-coupled parameter. It assumes that the physical characteristics of the stream are uniform over the distance shown, so that the decay coefficient (k), and the stream velocity (U) are constant. The equation describing the steady-state spatial characteristics of a non-conservative, non-coupled parameter with one source, under uniform conditions, is:

$$\bar{C}(x) = \frac{1}{\bar{Q}(x)} \left[\bar{C}(0)\,\bar{Q}(0)\, e^{-kx/\bar{U}} + \bar{C}_s(x_1)\,\bar{Q}_s(x_1)\, e^{-k(x-x_1)/\bar{U}} \right] \quad (3)$$

The non-conservative, coupled case is the most general mathematical form of the three categories of models. It can be reduced to either of the other two categories by appropriate choice of zero coefficients.

Because of the importance of dissolved oxygen to the quality of streams, the BOD-DO equations are used here to illustrate the non-conservative, coupled case. Figure 4 diagrams a case in which there is one new source of BOD and the stream conditions are uniform (i.e., the decay coefficients and stream velocities are constant). To simplify the model, distance is measured from the source in this illustration. The total BOD concentration (L (0)) in the stream immediately below the source (assuming immediate mixing, as before) is:

$$\bar{L}(0) = \frac{\bar{L}_0\,\bar{Q}_0(0) + \bar{L}_s\,\bar{Q}_s}{\bar{Q}_0 + \bar{Q}_s} \quad (4)$$

The dissolved oxygen is treated as a deficit concentration (D) referenced to the saturation concentration (C_{sat}):

$$\bar{D}(x) = \bar{C}_{sat}(x) - \bar{C}(x) \quad (5)$$

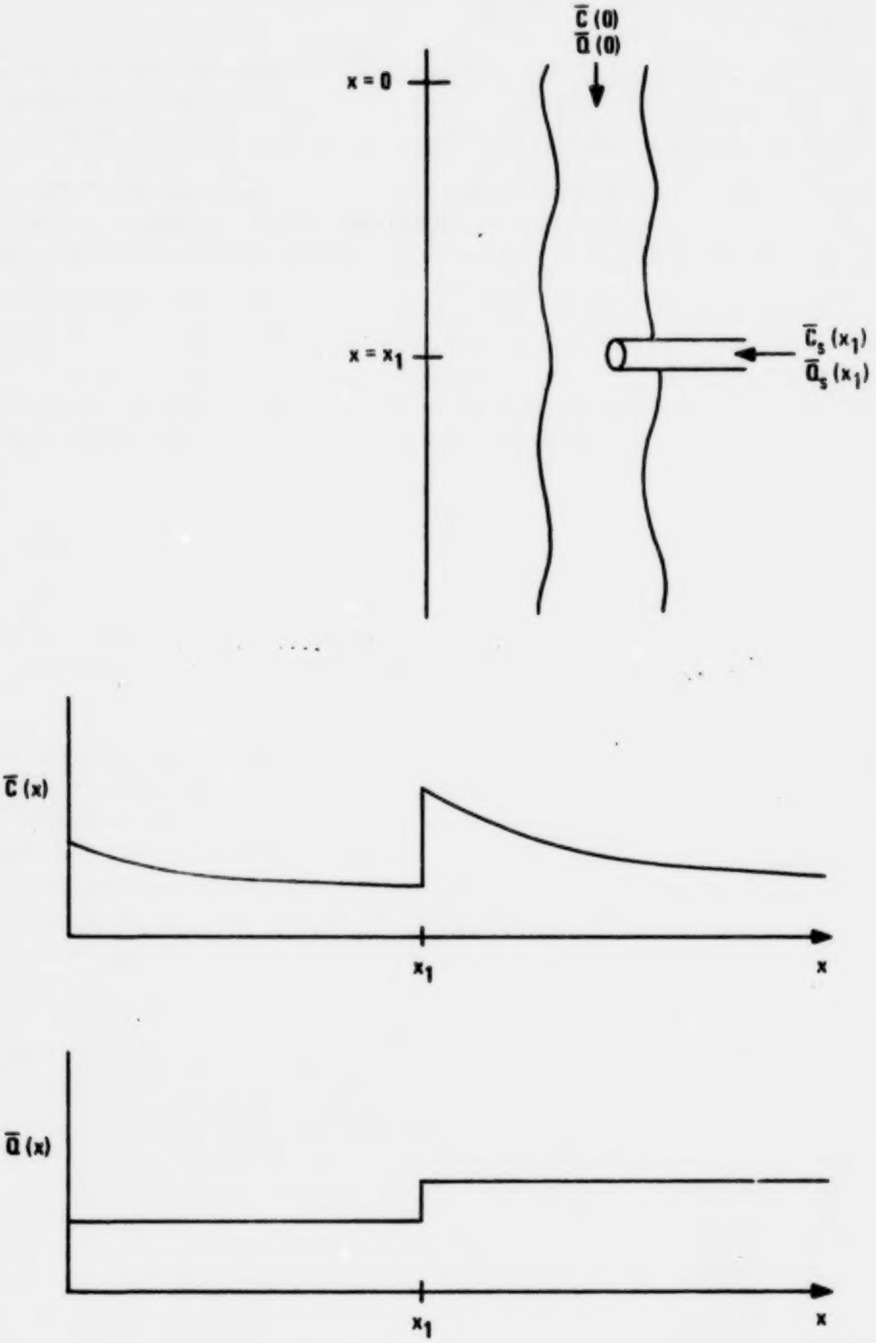


Figure 3. Illustration of Stream Characteristics for a Non-Conservative, Non-Coupled Parameter, Assuming Uniform Conditions

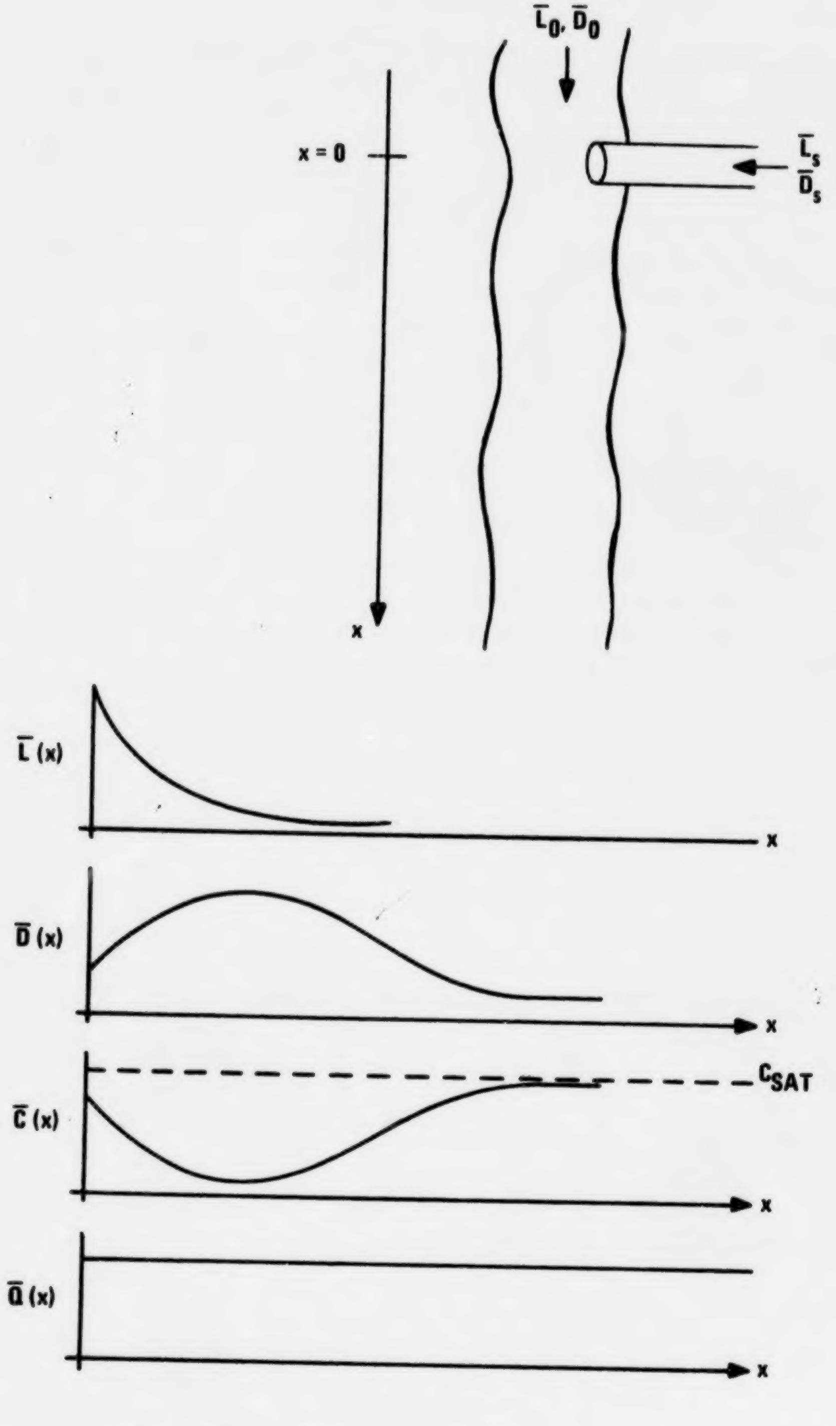


Figure 4. Illustration of Stream Characteristics For BOD-DO, Assuming Uniform Conditions

Thus, the DO deficit in the stream immediately below the source is:

$$\bar{D}(0) = \frac{\bar{D}_0 \bar{Q}_0 (0) + \bar{D}_s \bar{Q}_s}{\bar{Q}_0 + \bar{Q}_s} \tag{6}$$

And the equation giving the spatial characteristics of the DO deficit, under conditions of the one source, steady-state and constant coefficients, is:

$$\bar{D}(x) = \frac{k_d}{k_d - k_a} \bar{L}(0) \left[\exp\left(-\frac{k_d x}{\bar{U}}\right) - \exp\left(-\frac{k_a x}{\bar{U}}\right) \right] + \bar{D}(0) \exp\left(\frac{k_a x}{\bar{U}}\right) \tag{7}$$

where k_a = the oxygen reaeration rate coefficient

k_d = the BOD de-oxygenation rate coefficient.

It should be readily apparent from Equations (2), (3), and (7) that the downstream effect of any single source can be isolated from that of others influencing the concentration at that point. For example, the downstream effect of the BOD source alone (Figure 4) would be computed by:

$$\bar{L}'(0) = \frac{\bar{L}_s \bar{Q}_s}{\bar{Q}_0 + \bar{Q}_s} \tag{8}$$

$$\bar{D}'(0) = \frac{\bar{D}_s \bar{Q}_s}{\bar{Q}_0 + \bar{Q}_s} \tag{9}$$

$$\bar{D}'(x) = \frac{k_d}{k_d - k_a} \bar{L}'(0) \left[\exp\left(-\frac{k_d x}{\bar{U}}\right) - \exp\left(-\frac{k_a x}{\bar{U}}\right) \right] + \bar{D}'(0) \exp\left(-\frac{k_a x}{\bar{U}}\right) \tag{10}$$

and its relative effect ($\bar{R}$) at any point could be computed as:

$$\bar{R}(x) = \frac{\bar{D}'(x)}{\bar{D}(x)} \tag{11}$$

where $\bar{D}(x)$ is obtained from Equation (7). This relationship is used later in the discussion of "ultimate segment priority."

Estimation of Stream Characteristics

Estimation of the stream characteristics using Equations (2), (3) and (7) requires estimation of the various rates and coefficients. Information on stream flow ($\bar{Q}$), for example, may be gained directly from statistical analysis of the U.S. Geological Survey stream flow records. In contrast, estimates of velocity ($\overline{U}$) must be computed from the stream flow and a knowledge of the hydraulic cross-section of the stream. The rate coefficients for non-conservative parameters must be estimated from historical water quality data and a knowledge of stream velocity, by solving Equation (3) under carefully selected conditions. For example, the BOD decay rate coefficient (k_d) could be estimated by

$$k_d = \frac{\overline{U}}{(x_2 - x_1)} \ln \left(\frac{\overline{L}\,(x_1)}{\overline{L}\,(x_2)} \right) \tag{12}$$

where the $\overline{L}$'s are BOD concentrations in the stream and it is assumed there are no BOD discharges in the interval (x_1, x_2). The values for $\overline{U}$, x_1, x_2, and the $\overline{L}$'s are derived from historical water quality data. Methods for estimation of the necessary inputs to stream characterization are incorporated in the User Handbook (Appendix G).

Stream Segmentation

The application of the simple mathematical models used in quantitative preliminary design requires that the stream be divided into a number of segments. The stream segments are stretches of river along which the conditions which affect stream quality may be assumed to remain constant. Mathematically, this assumption means that the coefficients and certain of the independent variables (such as stream velocity and stream flow) are taken as constant throughout the segment.

Segmentation of the stream is done by isolating the geographical location of those stream features which modify stream conditions. The features may be either man-made or natural, ranging from industrial outfalls to the confluence of tributaries with the main stem. An identification of features requiring stream segmentation is contained in the User Handbook (Appendix G).

Use of the "macroscopic" concept in quantitative preliminary design requires that groupings of effluent sources be considered as point sources. This usage tends both to preserve the basin-level of design activity and to reduce the number of stream segments (reducing computational effort).

Establishment of outfall groupings is arbitrary, since the meaning of "a point source" is not precisely defined by the "macroscopic" concept.

However, any arbitrary rule employed in establishing groupings must be uniformly used throughout the basin. To promote uniformity of application, a quantitative rule should be used.

The User Handbook contains one such arbitray quantitative rule. The rule groups together all sources within a distance along the stream called the "tolerance length" (x_{tol}). The tolerance length is defined as the distance required for the parameter with the greatest rate of decay to reduce its concentration by 10%. (Another percentage could be selected by the system designer.)

The grouping rule is applied in a sliding fashion, beginning at the upstream end of the river. As groups are identified, the group impact on the stream is computed and compared with an arbitrary threshold. The threshold is set by the system designer at a level which defines a "major source". A decision that a group constitutes a major source defines the upstream end of a new stream segment (and, therefore, the downstream end of the previous segment).

It should be noted that the source grouping is done for all sources, regardless of water quality parameter affected by the source. While other computational steps in the quantitative preliminary design procedures are done for individual parameters, grouping considers all parameters.

The result of stream segmentation is that the mathematical models typified by Equations (2), (3) and (7) may be applied to each segment independently. The segment is considered to have two source inputs at its upstream end, one due to the preceding segment and the other due to the major source group which defines its beginning (Figure 5). All computations are, thus, performed with longitudinal distance (x) measured from the upstream end of the segment. If the length of the segment is x_E, then for conservative parameters, Equation (2) becomes:

$$\overline{C}\,(0 < x < x_E) = \frac{\overline{C}_0\,\overline{Q}_0 + \overline{C}_g\,\overline{Q}_g}{\overline{Q}_0 + \overline{Q}_g} \qquad (13)$$

where $\overline{C}_0$ = the mean concentration at the end of the preceeding segment

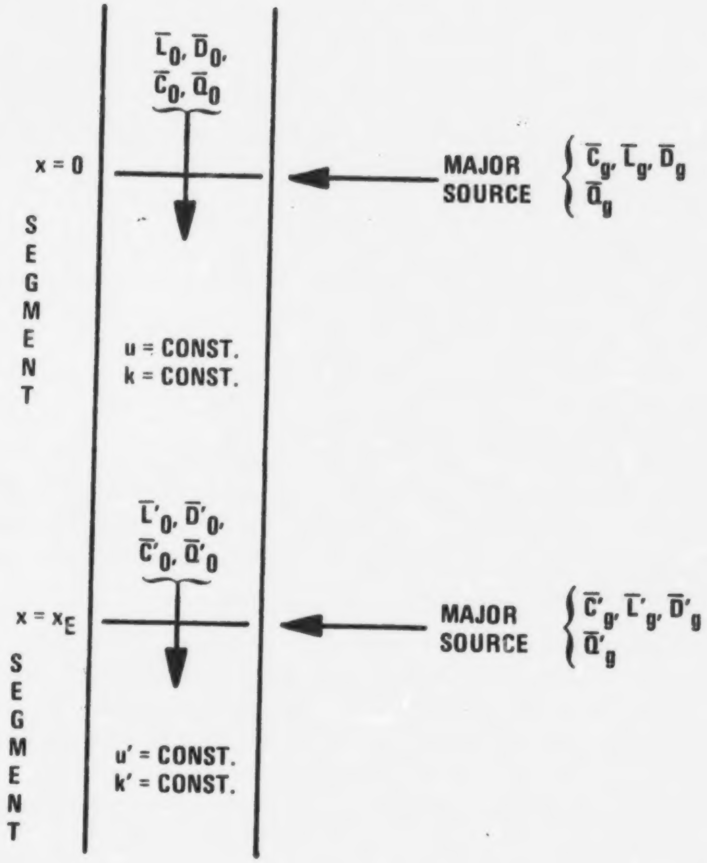
$\overline{C}_g$ = the equivalent mean concentration of the group effluent

$\overline{Q}_0$ = the mean stream flow at the end of the preceeding segment

$\overline{Q}_g$ = the total mean flow added by the source group.

In the case of non-conservative, non-coupled parameters, Equation (3) becomes:

$$C(x) = \frac{1}{\overline{Q}_0 + \overline{Q}_g}\left[\left(\overline{C}_0\overline{Q}_0 + \overline{C}_g\overline{Q}_g\right)\exp\left(-\frac{k_a x}{\overline{U}}\right)\right],\quad 0 < x < x_E \qquad (14)$$


$\overline{L}_0, \overline{D}_0, \overline{C}_0, \overline{Q}_0$
x = 0
MAJOR SOURCE
$\overline{C}_g, \overline{L}_g, \overline{D}_g, \overline{Q}_g$
SEGMENT
u = CONST.
k = CONST.
$\overline{L}'_0, \overline{D}'_0, \overline{C}'_0, \overline{Q}'_0$
$x = x_E$
MAJOR SOURCE
$\overline{C}'_g, \overline{L}'_g, \overline{D}'_g, \overline{Q}'_g$
SEGMENT
u' = CONST.
k' = CONST.

$$\overline{C}'_0 = \overline{C}\,(x_E) \text{ AND } \overline{Q}'_0 = \overline{Q}\,(x_E) = \overline{Q}_0 + \overline{Q}_g$$

Figure 5. Effect of Stream Segmentation

The BOD-DO equation (Equation (7)) remains as it was, because of the definitions used in writing it:

$$D(x) = \frac{k_d}{k_d - k_a} \overline{L}(0) \left[\exp\left(-\frac{k_a x}{\overline{U}}\right) - \exp\left(-\frac{k_a x}{\overline{U}}\right)\right] + \overline{D}(0) \exp\left(-\frac{k_a x}{\overline{U}}\right), 0 < x < x_E \tag{15}$$

where $\overline{L}(0) = \dfrac{\overline{L}_0 \overline{Q}_0 + \overline{L}_g \overline{Q}_g}{\overline{Q}_0 + \overline{Q}_g}$ (16)

and $\overline{D}\,(0) = \dfrac{\overline{D}_0 \overline{Q}_0 + \overline{D}_g \overline{Q}_g}{\overline{Q}_0 + \overline{Q}_g}$ (17)

Concept of Need to Monitor

The concept of need to monitor a particular segment is based on a judgment of the total benefit to be accrued from monitoring that segment. The total benefit has two components, one based on the worth to society of the information and the other based on the magnitude of new information to be gained. Each of these is discussed in the following paragraphs.

The establishment of the worth of information on water quality requires at least a qualitative judgment on the part of society which has not generally been made. Quantification of the worth is even less common. The problem of establishing the worth of information is not unique to water quality and various methods have been developed for establishing worth in specific cases. (See, for example, the development of "relative worth"curves based on "quantified expert judgment" described in [19] and [20] . See also [21].)

For the purposes of preliminary design of water quality surveillance systems, it is assumed that society has expressed its judgment of worth in terms of the federal-state water quality standards. The adopted standards are frequently referred to as "stream standards," because they apply to the waters contained in the open stream bed, rather than to effluents entering the stream. Typically, each stretch of a state's rivers is classified according to society's desired use of that stretch. Standards are then established for each stretch, based on scientific knowledge of the minimum water quality necessary to support the desired use. Where multiple uses are assigned, standards are based on the most sensitive use. Thus, it is taken that, in society's judgment, knowledge of any violation of the stream standards is a requirement of stream surveillance.

Since the use of such judgments in a quantified preliminary design procedure requires that they also be quantitative, a review of the existing federal-state water quality standards was undertaken. The objectives of the review were: 1) to determine the extent to which the stream standards were quantitative, and 2) the mathematical form of those standards which had been quantified. The latter objective was necessary in order to evaluate the impact of the standards on the mathematical formulation of the preliminary design procedure.

The detailed results of the review of stream standards are presented in Appendix B.

In summary, the level of quantification in stream standards varies widely from state to state, but standards for four of the water quality parameters are nearly always quantified. The parameters dissolved oxygen, coliform bacteria, pH, and temperature are consistently given in quantitative form, while the others are occasionally given numerical values. Of those standards which are quantified, the majority fall into the category described as "simple threshold." Examples of simple threshold are "temperature not to exceed 78° F at any time" and "dissolved oxygen not less than 5 mg/l at any time." The coliform bacteria standard was nearly always of the form "not to exceed a median of 1000 per 100 ml nor more than 2400 in more than 20% of samples collected." Based on the dominance of the simple threshold in the existing standards, it can be expected that future quantification of standards will be in that form predominantly. For example, individual chemical parameters are quantified infrequently in the present standards, but when quantified they are in simple threshold form. It may be expected that development of quantitative standards will continue to be in simple threshold form.

Thus, the stream standards constitute an acceptable quantified expression of society's judgment of the worth of information on the status of a stream segment. The standards reflect society's desired uses of the stream, its interest in protecting those uses, and its understanding of the minimum conditions necessary to support those uses. It may be assumed that it is highly important to have knowledge of those occasions when the stream fails to meet those minimum conditions.

The way in which the stream standards are used to compute the priority (the need for measurement) of a stream segment is detailed in the development of the priority rating procedure, which is found later in this section.

The priority rating procedure is based solely on the simple threshold form of the standards. This choice is made because of the dominance of that form in the standards. Existing standard procedures may be used to establish monitoring for the case of coliform bacteria [22, 23, 24]. For purpose of system design, other forms of the standards can be reduced to the simple threshold form.

The other factor affecting the need to monitor a particular segment of a stream is the expected net gain of information. The net gain in information is the amount of new information to be acquired by establishing surveillance of the segment. Net gain can be minimized by the existence of stream surveillance in the vicinity of the location specified by the quantitative procedure. Such stream surveillance may be associated either with a previous monitoring network which will continue to function, or with the system under design. In the latter case, a decision to establish surveillance in one segment of the stream may reduce the relative need to monitor neighboring segments. Detection of a violation in an upstream segment may provide a warning of impending violation in a segment downstream, or it may indicate worsening conditions further upstream.

Thus, the need to monitor a particular segment must be weighted by the likelihood that sufficient information on the segment may be available from other sources. The weighting is based on the relative dependence of water quality in the segment on conditions at stations already being monitored.

Segment Priority

The quantitative measure of need to monitor a stream segment for a parameter is called, in general, the "segment priority." For purposes of discussion, segment priority has been separated into two portions, one associated with the absolute worth of information on the stream segment, the other associated with the relative worth of the information, as discussed above. The priority associated with absolute worth is termed the "initial segment priority." When consideration of the relative worth is included, the combined measure is called "ultimate segment priority."

Initial Segment Priority

The initial segment priority (P) is a function of the expected condition of the stream segment and the desired condition of the stream , as expressed by the applicable water quality standards.

The definition of initial segment priority is based on the concept of probability of violation. The need to monitor a segment may be measured by the maximum probability that a violation will occur in the segment, under consideration (π_V). However, as shown below, it is not necessary to carry out the computation of probability in order to establish the initial segment priority. For the purposes of quantitative preliminary design of water quality surveillance systems, (see Appendices C and D) the initial segment priority (P) may be defined as:

$$P \equiv \begin{cases} \dfrac{C_T - \overline{C}_m}{\sigma_c} & \text{for NLT thresholds} \\[2ex] \dfrac{\overline{C}_m - C_T}{\sigma_c} & \text{for NTE thresholds} \end{cases} \qquad (18)$$

where $\overline{C}_m$ = the expected worst case (maximum or minimum) value of the parameter concentration in the segment.

C_T = the standards threshold in the segment

σ_c = the expected standard deviation of the parameter concentration in the segment

NLT = "not less than"

NTE = "not to exceed"

The properties of this formulation are shown in the appendices to constitute a sufficiently good representation of π_v. In summary, the priority has a possible range of $-\infty$ to $+\infty$, but the range is somewhat limited in practice by physical properties such as saturation values and zero concentration. The lowest priority segments may have negative priorities, corresponding to probability of violation less than 0.5. A positive priority implies a relatively high need, with a probability of violation greater than 0.5. See Figure 6 for a graphical interpretation of the relationship between P and π_v. Computation of actual segment priorities is based on the estimation of $\overline{C}_m$ and σ_c. Methods for estimation of these quantities are explored in Appendix D. The average (expected) worst case value of the parameter may be estimated from knowledge of the average source load, stream flow and contribution from the upstream segment. For dissolved oxygen, for example, the estimator for $\overline{C}_m$ derived from Equations (5) and (15) is:

$$\overline{C}_m = \overline{C}(x_m) = \overline{C}_{sat} - \overline{D}(x_m) = \overline{C}_{sat} - \overline{L}(0)\, A_1(x_m) - \overline{D}(0)\, A_2(x_m) \qquad (19)$$

where $A_1(x_m) = \dfrac{k_d}{k_a - k_d}\left[\exp\left(-\dfrac{k_d x_m}{\overline{U}}\right) - \exp\left(-\dfrac{k_a x_m}{\overline{U}}\right)\right]$

$A_2(x_m) = \exp\left(-\dfrac{k_a x_m}{\overline{U}}\right)$

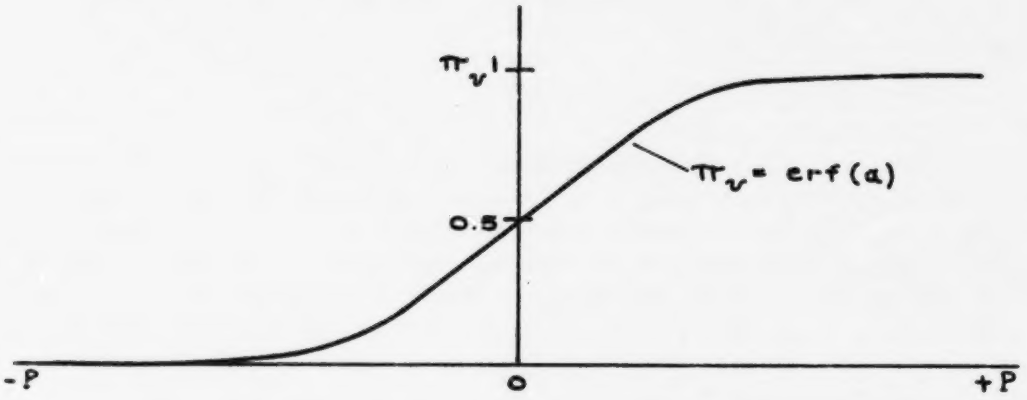


Figure 6. Probability of Violtation (π_v) as a Function of P.

As before, estimates of $\overline{L}$, $\overline{D}$, $\overline{U}$, k_d and k_a are obtained from the available historical data. Estimation of the location (x_m) of the maximum probability of violation is discussed below. Estimation of the standard deviation is handicapped by a general lack of available data on the variability of source loads. For dissolved oxygen, for example, analysis of Equation (15) yields the relationship:

$$\sigma_c = \left[A_1^2 \sigma_{L_0}^2 + A_2^2 \sigma_{D_0}^2 + \left(A_1^2 \overline{L}_0^2 + A_2^2 \overline{D}_0^2 \right) \sigma_U^2 \right]^{1/2} \qquad (20)$$

Evaluation of this equation requires a knowledge of σ_{L_0} and σ_{D_0} not generally available, Due to the typical difficulties in estimating σ_c based on the relationship of Equation (20), it has been necessary to use the standard deviations computed directly from STORET data. While this is not entirely satisfactory from a statistical viewpoint, it appears to give sufficiently good results to be useful. In effect, the standard deviation operates as a scaling factor for the range of variation. To that extent, any estimator consistently used to provide scaling of the correct order of magnitude for each parameter is satisfactory. See Appendix D for the details of the estimation process.

Location of Point of Maximum Violation Probability

Computation of the segment priority is based on the maximum probability of violation found in the segment. While the segment priority is estimated by computation of the quantity P (Equation (18)), the values used in the computation are those found at the point of maximum probability.

Thus, a prerequisite of the segment priority computation is location of the point of maximum probability of violation.

The location of the maximum point will vary according to the parameter and the physical characteristics of the stream. Factors affecting the location are the variation of the parameter mean and the standard deviation along the length of the segment. The probability of violation increases as the temporal mean value of the parameter approaches (or exceeds) the water quality standards threshold. This is illustrated in Figure 7 for the gaussian distribution, which is assumed to describe the temporal variability of water quality parameters (Appendix C). The area under the curve and below the NLT threshold is directly proportional to the probability of violation. The case of standard deviation is somewhat more complex, since it depends both on the standard deviation and the value of the mean with respect to the threshold. For those cases in which the mean is not in violation of the standard, the probability of violation increases with increasing standard deviation. Figure 8 illustrates this case. When the mean of the parameter is normally in violation of the standards, an increased standard deviation tends to decrease the probability of violation, as illustrated in

Figure 9. These relationships are preserved in the use of the quantity P to represent the segment priority.

However, computation of P is accomplished by use of fixed σ_c in each segment. The rationale for this choice has been discussed above.

Under this circumstance, it can readily be seen that the location of maximum violation probability coincides with the location of maximum (or minimum, depending on the type of threshold) temporal mean parameter concentration.

For conservative parameters, the time-average concentrations is taken as constant throughout each segment (Equation (13)). Computation of the segment priority may be based on the value of mean concentration, without regard for location.

Non-conservative, non-coupled parameters typically have a maximum concentration at the upstream end of each segment, closest to the source (Equation (14)). Computation of segment priority is, thus, based on the value at the upstream end of the segment, for non-conservative, non-coupled parameters.

The case of non-conservative, coupled parameters requires some attention. These parameters may have an extremum anywhere in the segment, with the location dependent on a number of factors (Appendix D). For the BOD-DO case typical of this category of parameters, the point of minimum concentration (since it is a NLT parameter) is found by:

$$\overline{x}_m = \begin{cases} 0 & \text{for } \overline{x}_c < 0 \\ \overline{x}_c & \text{for } 0 < \overline{x}_c < x_E \\ x_E & \text{for } \overline{x}_c > x_E \end{cases} \tag{21}$$

where

$$\overline{x}_c = \frac{\overline{U}}{k_a - k_d} \ln \left\{ \frac{k_a}{k_d} + \frac{(k_a - k_d)\, k_a\, \overline{D}_0}{k_d^2\, \overline{L}_0} \right\} \tag{22}$$

Ultimate Segment Priority

Ultimately, the need to monitor a particular segment is a function not only of the likelihood of a violation occuring in the segment, but also of the information available from monitoring neighboring segments. If the occurence of violations in two segments is highly correlated, then it is possible to monitor only one of them without significant loss of information on the others.

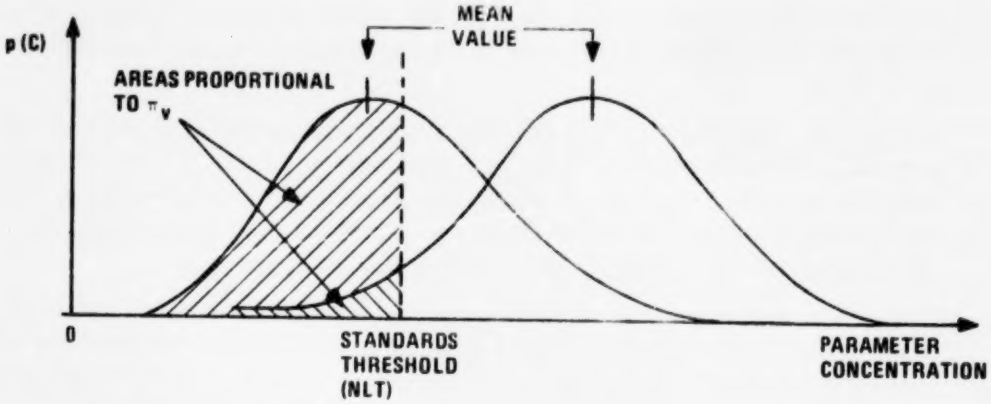


Figure 7. Comparison of Probability of Violation (π_v) for Varying Parameter Means, with Standard Deviation Constant

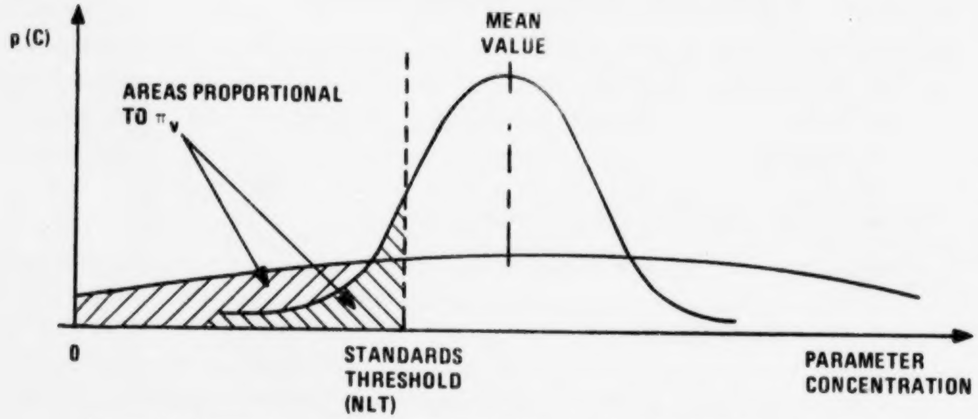


Figure 8. Comparison of Probability of Violation (π_v) for Varying Standard Deviations, with Mean not in Violation of Standard

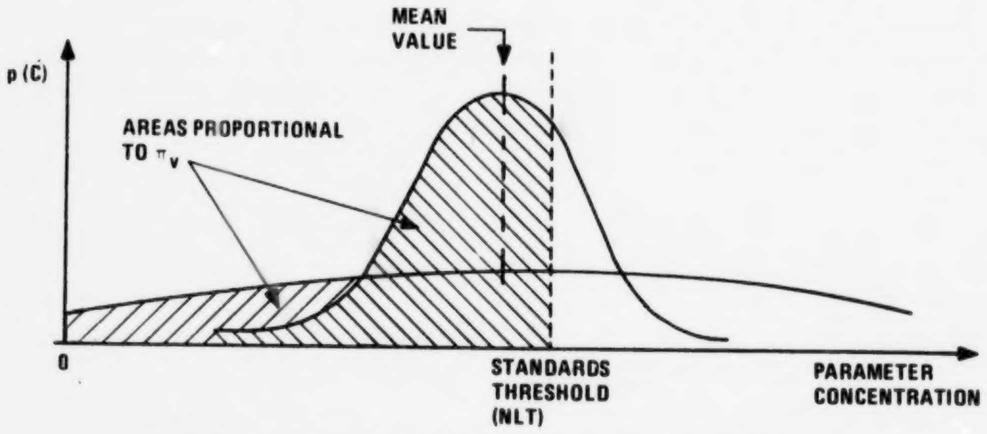


Figure 9. Comparison of Probability of Violation (π_v) for Varying Standard Deviation, with Mean in Violation of Standard

Theoretically, it is possible to compute the statistical cross-correlation between every pair of segments in the river basin and to adjust the segment priority accordingly.

Practically, however, it is not feasible to compute the ultimate segment priority according to the theoretical approach. Computation of the true statistical correlation is limited by the lack of information necessary to its calculation. Even if sufficient information were available, the use of P as the segment priority does not require direct application of the true statistical correlation.

It should also be noted that the calculation requirements for computation of ultimate priority are extreme. For a basin containing n segments there are $(n^2-n)/2$ cross-correlations. If m of those segments were included in existing surveillance, the number of adjustments of segment priority would be $\sum_{i=1}^{m} (n-i)$, each involving numerous individual steps, since the priority of every remaining segment must be adjusted as each new station is added.

An estimation method has been developed to facilitate the actual computation of the ultimate segment priority. The estimation method has been incorporated in the preliminary design procedure detailed in Appendix G. Its development is described next.

Estimation of Ultimate Segment Priority

There are two aspects to the estimation of the ultimate segment priority. One is replacement of the cross-correlation with a method which is both calculable from the available information and compatible with the use of P to represent segment priority. The other aspect is the limitation of the total number of computational steps required to calculate ultimate segment priority. Both aspects are satisfied by the method incorporated in the User Handbook (Appendix G).

It is shown above (see, for example, Equations (8), (9), (10) and (11)) that the impact of individual sources can be isolated from that of others influencing the water quality at a point. Thus, it is possible to eliminate from the computation of P that portion of $\overline{C}_m$ which is due to the water quality in a segment under surveillance. Defining P* as the ultimate segment priority gives:

$$P_i^* \equiv \begin{cases} \dfrac{C_T - \overline{C}_m^*}{\sigma_c} & \text{for NLT thresholds} \\ \dfrac{\overline{C}_m^* - C_T}{\sigma_c} & \text{for NTE thresholds} \end{cases} \qquad (23)$$

where $\overline{C}_m^* = C_m (1 - R_{iq})$

The quantity R_{iq} is an estimator for the cross-correlation between the ith segment and the qth segment, which is under surveillance. For adjacent segments, the quantity R_{ij} is computed as in Equation (11):

$$R_{ij} = \frac{\overline{C}_m^{\,i}}{\overline{C}_m}, \quad i = j - 1 \tag{24}$$

where the superscript i indicates the portion of C_m which is due to the upstream segment. As a result of defining R_{ij} in this way, it can be shown that, for most cases:

$$R_{ik} = R_{ij} R_{jk}, \; i = j - 1 = k - 2 \tag{25}$$

Equation (25) holds exactly for conservative parameters and for non-conservative non-coupled parameters. It also holds for some cases of the non-conservative, coupled parameters for example, when one of the two terms in Equation (10) dominates. For purposes of preliminary design, it is taken that the relationship is at least approximately true for all cases.

Thus, use of the above relationship reduces the computation of $(n^2 - n)/2$ cross-correlations to computation of $(n - 1)$ values of R_{ij} $(i = j - 1)$ and calculation of $(n - 1)^2/1$ products $R_{ij} R_{jk}$ $(i = j - 1 = k - 2)$. Furthermore, it can be seen that R_{ij} is very nearly zero for all but the closest segments. This significantly reduces the number of actual adjustments of priority which must be made, as selection of segments to be monitored progresses.

Station Location

Under the preceeding analysis, the selection of the location for monitoring each parameter in each segment becomes a trivial task. Since the objective of the surveillance system is the detection of water quality violations, observations should be taken at the point of maximum probability of violation in the segment. The preferred station location for each parameter in a segment, thus, coincides with the point at which the segment priority is computed. Conservative parameters may be sampled anywhere within the segment. Stations near the upstream end of the segment are established for non-conservative, non-coupled parameters. Because this location typically is an outfall location, the practical application of most standards requires the station be located outside of, but immediately adjacent to, the mixing zone (Appendix B). For non-conservative, coupled parameters, the preferred station location may vary along the length of the segment and is identified by use of Equations (21) and (22). Again, when the station is near the upstream end of a segment, cognizance must be given to the mixing-zone requirement.

Development of the Procedure for Selection of Sampling Frequency

The procedure for establishing appropriate sampling frequencies differs from the procedure for establishing segment priority in that it yields a priority measure describing the relative "goodness" of sampling frequencies. It does not tend to select a preferred frequency, since the measure continuously improves with increasing frequency of observation.

Because of this feature of the sampling frequency priority measure, it is ideally used in conjunction with a cost-effectiveness analysis. Used in that way, it tends to measure the effectiveness of the sampling scheme. Balancing effectiveness against cost may be expected to yield a unique preferred sampling frequency.

In the following paragraphs, the development of the priority measure used to rate candidate sampling frequencies is summarized. The surveillance system objectives are reviewed and the priority measure defined in relation to those objectives. A mathematical expression for the measure is given and the limiting forms of the expression examined. The measure is contrasted with more traditional sampling theory. Based on these discussions and an analysis of the practical aspects of computation, a procedure for rating candidate sampling frequencies is presented.

Definition of Priority Measure for Sampling Frequency

The priority measure for sampling frequency (M) is defined as the expected percentage of violations of water quality standards that are detected, or more precisely:

$$M = \frac{\text{Expected Number of Violations Detected}}{\text{Expected Number of Violations}}$$

The definition is stated in terms of only one of the major objectives of water quality surveillance systems, abatement, but the resulting sampling schemes are sufficient to the other major goal, planning (or prevention, [1]).

The necessity for this measure to be quantitative is clear. It is intuitively obvious that, by increasing the sampling frequency, more surveillance information is obtained, so that higher frequencies should be rated better than lower frequencies. It is not obvious how much better a higher frequency is. Thus, a priority measure is needed which is a quantitative measure of sampling effectiveness.

Mathematical Expression for Sampling Frequency Priority Measure

An expression of the priority measure M in terms of the sampling interval, Δ, (the reciprocal of the sampling frequency), the expected average duration of a violation, T_1, and the expected average interval between violations, T_0, is

$$M(\Delta, T_0, T_1) = \frac{T_0}{\Delta} \left[C_0 \exp(-\Delta/T_0) + C_1 \exp(-\Delta/T_1) \right] \tag{26}$$

where:

$$C_0 = \sum_{n=1}^{\infty} \frac{T_0^{\,n-1} \; T_1^{\,n}}{(T_0 - T_1)^{2n-1}} \; f_{0n} \, ,$$

$$C_1 = \sum_{n=1}^{\infty} \frac{T_0^{\,n-1} \; T_1^{\,n}}{(T_0 - T_1)^{2n-1}} \; f_{1n} \, ,$$

$$f_{0n} = \sum_{k=1}^{n} a_k^n \; \Delta^{k-1} \left[\frac{T_0 - T_1}{T_0 \, T_1} \right]^{k-1} ,$$

$$f_{1n} = \sum_{k=1}^{n} b_k^n \; \Delta^{k-1} \left[\frac{T_0 - T_1}{T_0 \, T_1} \right]^{k-1} ,$$

$$a_k^n = \frac{(-1)^{n-k} \; (2n-k-1)!}{(n-k)! \; (n-1)! \; (k-1)!} \, ,$$

$$b_k^n = (-1)^k \, a^n \, ,$$

and $\Delta < T_0$ is assumed.

Equation (26) is based on consideration of the probability of sampling a violation event under the assumption that such events are Poisson processes. The detailed derivation of this expression is presented in Appendix E.

The expression can be approximated by a less complex form, for $\Delta < T_0 + T_1$:

$$M(\Delta, T_0, T_1) \approx M^*(\Delta, T_0, T_1)$$

$$\approx \frac{T_0}{\Delta} \left[\frac{\exp(-\Delta/T_0) - \exp(-\Delta/T_1)}{(T_0/T_1) - 1} \right] \tag{27}$$

The condition under which this approximation holds, $\Delta < T_0 + T_1$, is the case of most interest. It states that the sampling interval is less than the expected average time between violation incidence. The condition is true for all cases in which a high percentage of violations are to be detected, i.e. $M > 50\%$.

The expression $M^* (\Delta, T_0, T_1)$ is plotted in Figure 10 as a function of relative sampling interval (Δ / T_1) for several values of T_0/T_1. As Δ / T_1 becomes small, M^* approaches unity, as expected, since the probability of at least one sample being taken during each violation is close to one when Δ is small relative to T_1. Also, as T_0/T_1, becomes large, corresponding to a small probability of violation, the measure M^* becomes dependent solely on Δ/T_1 (and independent of T_0), as would be expected.

The curves shown in Figure 10 constitute the essential element in the procedure for rating candidate sampling frequencies. Using the curves, the quantitative improvement in sampling effectiveness can be found for any sampling interval (frequency). A graphical procedure is feasible, because M^* is a function only of the two parameters Δ/T_1 and T_0/T_1.

Contrast with Spectral Methods

The sampling theory presented here and in Appendix E contrasts with the spectral methods which are commonly used to establish sampling frequencies [25] .

In the spectral approach, the designer bases selection of the sampling frequency on an estimate of the power spectrum of the process and the maximum acceptable error [26] . Nyquist sampling theory indicates that variations at frequencies greater than the Nyquist frequency (f_N) will appear as an "error" at lower frequencies. Since a direct relationship exists between the Nyquist frequency and the sampling frequency $(f_N = 1/2 \, f_s)$, the designer may select the sampling frequency to reduce the expected "error" to an acceptable level (Figure 11). The spectral approach can provide information about the "goodness" of a particular sampling rate at portraying the original process. It cannot provide information about the ability of a sampling scheme to detect particular conditions of that process, such as a violation condition. This limitation is due to the elimination of phase information in the computation of the power spectrum.

Thus, while the spectral approach is an excellent means of designing sampling systems to protray the full variation of the original process, it is not useful in designing sampling systems to detect only discrete states of the original process.

A sampling scheme designed on the basis of spectral methods may detect violations, of course. There is, however, no way of measuring the likelihood

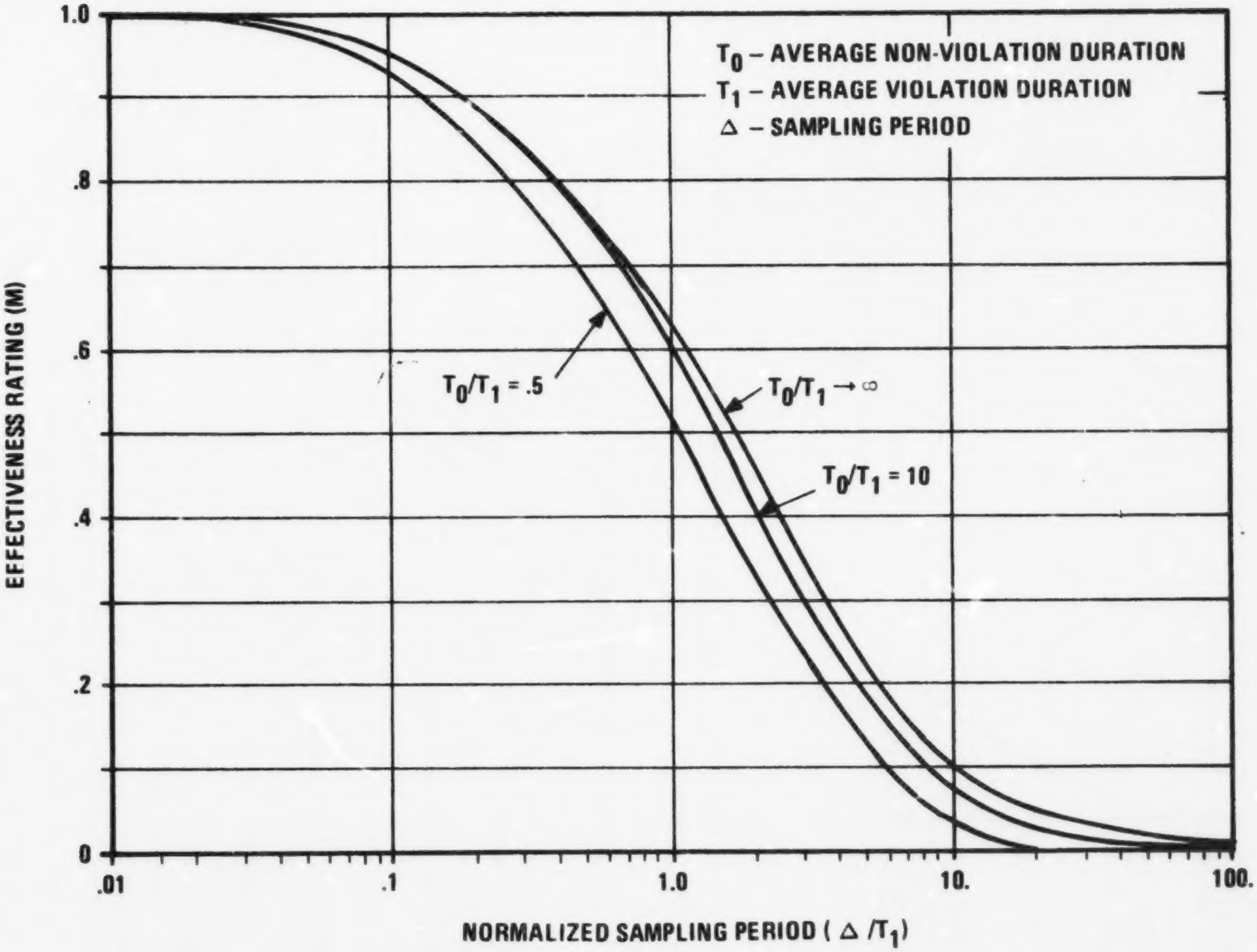


Figure 10. Temporal Effectiveness Rating as a Function of T_1, T_0 and Δ.

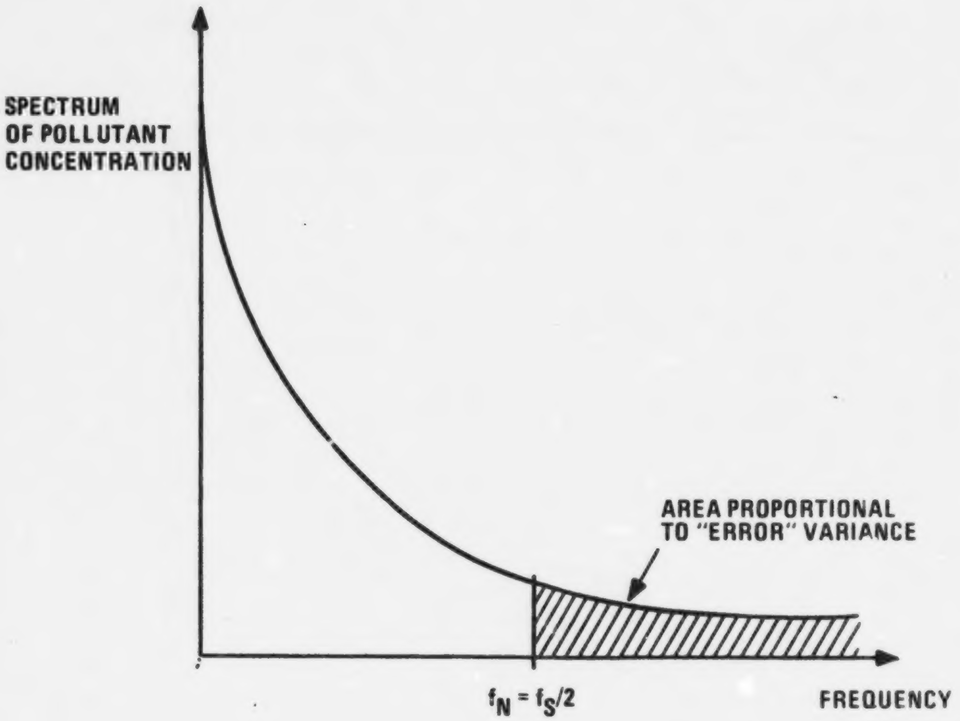


Figure 11. Typical Pollutant Spectrum Showing Effect of Sampling

of such detection using the spectral method. Even if sufficient water quality data were available to allow system design based on spectral methods, application of those methods to design of systems solely to detect water quality violations is not a preferred approach.

Estimation of the Sampling Frequency Priority Measure

Estimation of the sampling frequency priority measure (M) is dependent on estimation of the expected durations, T_0 and T_1. Obtaining estimates of T_0 and T_1 requires relatively detailed data on the historical stream quality and waste load characteristics, at least daily observations over a number of years. Such high frequency data on both stream and effluent characteristics is not generally available. Long records of daily stream flow are available through the U.S. Geological Survey for every minor river basin in the country. A method of estimating T_0 and T_1 based on the streamflow records is presented in Appendix F and incorporated in the User Handbook (Appendix G).

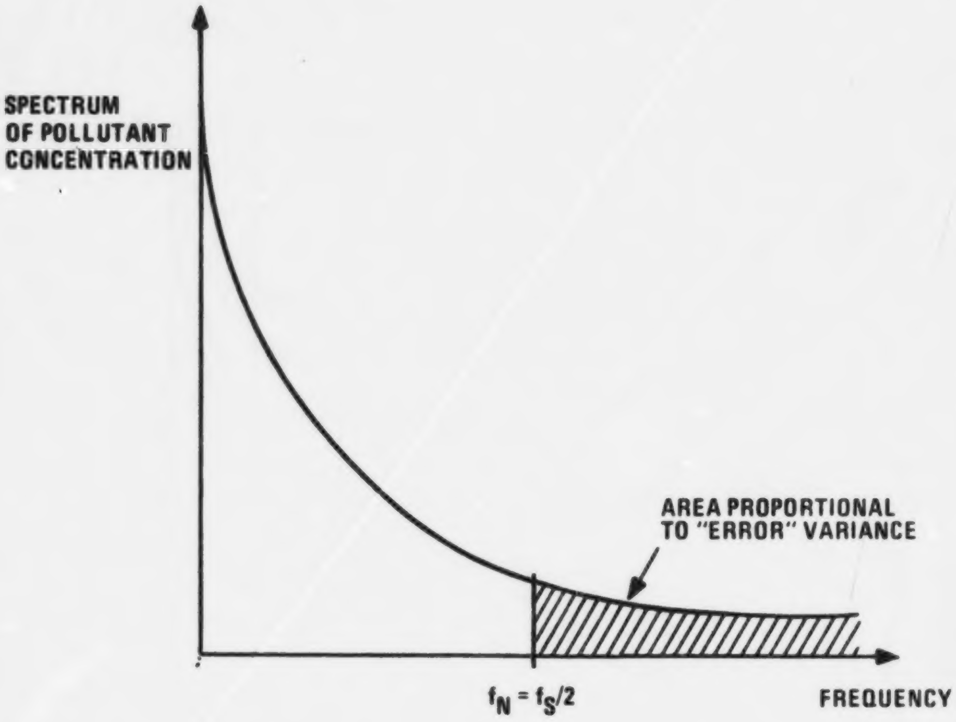


Figure 11. Typical Pollutant Spectrum Showing Effect of Sampling

of such detection using the spectral method. Even if sufficient water quality data were available to allow system design based on spectral methods, application of those methods to design of systems solely to detect water quality violations is not a preferred approach.

Estimation of the Sampling Frequency Priority Measure

Estimation of the sampling frequency priority measure (M) is dependent on estimation of the expected durations, T_0 and T_1. Obtaining estimates of T_0 and T_1 requires relatively detailed data on the historical stream quality and waste load characteristics, at least daily observations over a number of years. Such high frequency data on both stream and effluent characteristics is not generally available. Long records of daily stream flow are available through the U.S. Geological Survey for every minor river basin in the country. A method of estimating T_0 and T_1 based on the streamflow records is presented in Appendix F and incorporated in the User Handbook (Appendix G).

It should be noted that the estimation method is inappropriate in low priority segments. This is due to failure of the available data records to meet the minimum sample size requirement when the probability of violation is low. Under conditions of low probability of violation, the chance of actually observing a violation condition in the data record becomes extremely small. Estimation of the T_0 and T_1 requires observation of at least one violation event.

Establishment of Sampling Frequency in Pristine Waters

Establishment of sampling frequency in segments with very low priority should be based on prevention objectives, not abatement objectives. Satisfaction of prevention objectives requires observation of long-term trends to detect degradation of high quality water. Ward [1] has explored standard statistical techniques for establishing sample size and developed a method of determining sampling frequency effectiveness under the prevention goal. Ward's method assumes that all samples are drawn from a normally distributed population. Using this assumption, he then computes the number of samples necessary to yield an estimate of the parameter value to within predetermined confidence limits. By assuming these samples are to be obtained over a known period of time, he arrives at a sampling rate. These methods have been incorporated into the User Handbook (Appendix G), without further development.

Multiple Parameter Design

Until this point in the development, the discussion has been directed toward establishing the priority, station location and sampling frequency for a single parameter. In application, the user will probably be concerned with design of a surveillance system for more than one parameter [27, 28, 29, 30]. The application of the design procedure to the multi-parameter case should be done in the context of a cost-effectiveness trade-off. It can be seen from the preceeding discussion that segment priority, station location and sampling frequency are dependent on the parameter under consideration. A given segment may have as many preferred station locations and priorities as there are parameters of interest to the designer. The decision as to which of these to implement is a function not only of the priority, but also of the expected cost of implementation and the anticipated benefit. For example, collection of a grab sample for analysis of a high priority parameter may permit additional analysis for low priority parameters. Alone, the low priority parameters might not justify acquisition of the sample, but in conjunction with a high priority parameter they may become cost-effective.

However, for purposes of preliminary design, it may be of interest to consider only the comparative weights of the various parameters. To further such comparison, the following points are made:

1) Because of the inherent normalization, the segment priority for each parameter may be directly compared with that for other parameters. A more positive (or less negative) segment priority indicates a proportionally higher probability of violation than the parameter to which it is being compared.

2) The computation of correlations is performed on a parameter by parameter basis, just as the initial segment priority is. When a station is established, the computation of new ultimate segment priority is done only for the parameters to be sampled at that station.

3) An aggregate segment priority can be computed for each segment as the average of the individual segment priorities for each parameter in the segment. It should be recognized that such aggregate segment priorities must be re-computed by re-averaging as each new station is established, since the application of correlations is on a parameter-by-parameter basis.

4) The comparison between sampling frequency for each parameter is also direct, due to the inherent normalization. The effectiveness of a given sampling frequency is a function not only of the frequency, but also of the parameter. Thus, two parameters sampled at the same frequency may have significantly different effectiveness ratings.

Use of Available Data

Finally, it is emphasized that the methods of estimation developed in this section are founded on the requirement that they be generally applicable. Such a constraint tends to produce methods which may be used with the minimum data available.

The user should make every effort to include the best data available in his preliminary design. Where the existing procedures detailed in the User Handbook do not accommodate higher quality data, modifications should be made compatible with the general theoretical basis for the method, as described in this section and Appendices A through F.

SECTION VII

DEMONSTRATION OF QUANTITATIVE METHODS

The major features of the quantitative preliminary design procedure are successfully demonstrated on portions of the Wabash River Basin in this section. The procedure is demonstrated for BOD-DO on both the Wabash River and its tributary, Wildcat Creek. It is also demonstrated for a conservative parameter, fluorides, on Wildcat Creek alone.

The Wabash River Basin was selected by the EPA as the basin on which the quantitative preliminary design procedure would be demonstrated. It was stipulated that the procedure would be demonstrated on the Wabash mainstem and one of its tributaries. Wildcat Creek was selected as the tributary on the basis of the recognized degradation of water quality in the stream.

Following some introductory remarks concerning the validity of the demonstration results and an overview of the Wabash River Basin, the presentation follows the order of activity found in the User Handbook (Appendix G). The reader may use this section of the report as a step-by-step illustration of the application of the quantitative preliminary design procedure.

The preliminary design of the surveillance system is aimed at providing a monitoring capability on only the Wabash River and Wildcat Creek. Thus, these two streams compose the basin subset, as defined in the User Handbook (Appendix G).

Caveat

The objective of this section is the demonstration of the quantitative procedures for preliminary design of water quality surveillance systems. The selection and use of the Wabash River Basin to further this objective should not be construed as an expression of opinion concerning the status of the Wabash River or its tributaries. The results of the demonstration are based on a careful application of the design procedure to the data available. The authors have made every attempt to assure that the data used is exhaustive and representative, but they recognize the possibility that relevant information may have been overlooked. To this extent then, the results of the demonstration may be considered directly applicable to evaluation of water quality surveillance on the Wabash River and Wildcat Creek.

The Wabash River Basin

The Wabash River Basin lies predominantly in the states of Indiana and Illinois, encompassing approximately 2/3 of Indiana and approximately 1/6 of Illinois

(Figure 12). The mainstem of the Wabash forms the southern portion of the boundary between the two states. A much smaller area of the basin (approximately 319 square miles) lies in Ohio, where the Wabash River originates. The total area drained is approximately 33,100 square miles. A population of about 3.1 million lived in the basin in 1960. Principal industrial centers in the basin include Indianapolis, Champaign-Urbana, Terre Haute, Kokomo, and Muncie [30].

The Wabash River is a major tributary of the Ohio River, normally adding about 30,000 cubic feet per second to the flow in the Ohio. Major tributaries to the Wabash include the Salamonie, the Mississinewa, the White, the Patoka, the Embarras, and the Little Wabash Rivers [31]. While the Wildcat is not usually considered a major tributary, it is significant and drains the industrialized area surrounding Kokomo, Indiana.

Task One Activities

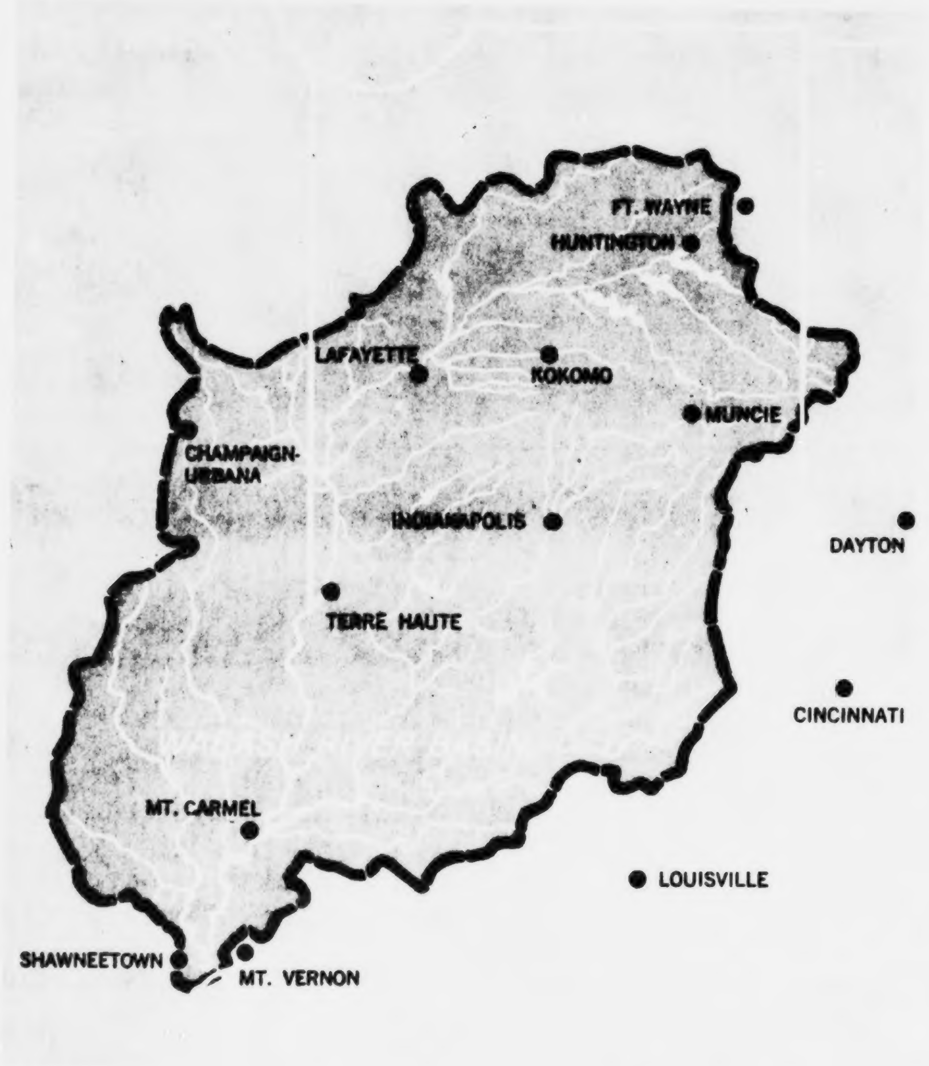
The first task in preliminary design of water quality surveillance systems is primarily organizational. Included in the task are map gathering, standards identification, data organization, and selection of constraints that will guide subsequent activity.

The federal-state standards for the Wabash River and Wildcat Creek are established by Indiana, Illinois, and Ohio. Those applicable to the demonstration are contained in Table 1, which is derived from those standards [32, 33, 34].

Data on the Wabash River and Wildcat Creek were obtained from several sources. The EPA STORET system provided a number of types of data, including:

- Summaries of all data in STORET for the Wabash River Basin (Figure 13 is typical).
- Detailed listings of individual data entries on specific water quality parameters (Figure 14 is typical).
- Inventories of municipal wastewater treatment facilities for the Wabash Basin (Figure 15 is typical).
- Inventories of industrial wastewater treatment implementation plans for the Wabash Basin. These include the SIC codes and planned effluent flows (Figure 16 is typical).

The U.S. Geological Survey (USGS) provided data on stream flows through their publications "Water Resource Data for Indiana," "Water Resource Data



Reproduced from best available copy.

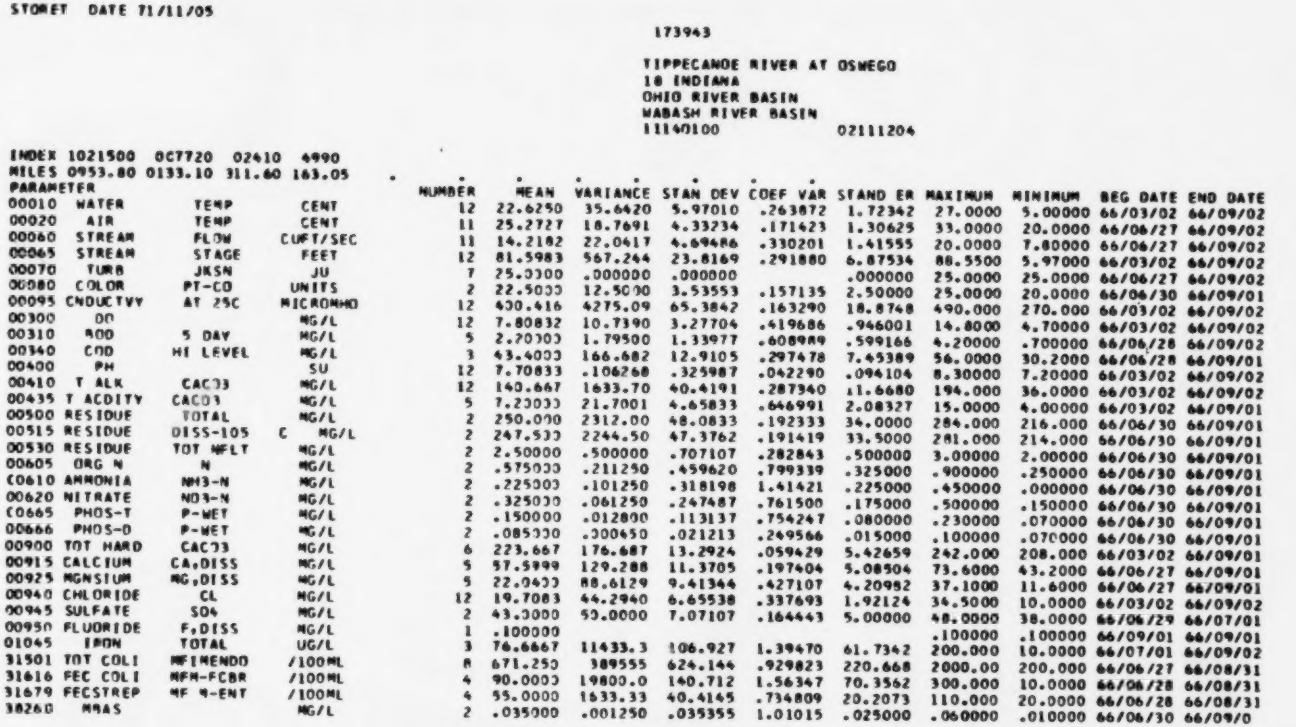
Figure 12. Wabash River Basin Overview (from [31])

Table 1. Standards for Dissolved Oxygen and Fluorides Applicable to the Wabash River and Wildcat Creek

State	Classification	Dissolved Oxygen	Fluorides
Ohio	PWS	No Standard.	(Not Applicable)
	IWS	Not less than 2.0 mg/l as a daily average, nor less than 1.0 mg/l at any time.	(Not Applicable)
	AL(A)	Not less than an average of 5.0 mg/l per calendar day and not less than 4.0 mg/l at any time.	(Not Applicable)
	AL(B)	Not less than 3.0 mg/l as a daily-average value, nor less than 2.0 mg/l at any time.	(Not Applicable)
	REC	No Standard.	(Not Applicable)
	AG	No Standard.	(Not Applicable)
Indiana	PWS	No Standard.	Not to exceed 1.0 mg/l at any time
	IWS	Not less than 2.0 mg/l as a daily average value, nor less than 1.0 mg/l at any time.	No Standard
	AL	Average at least 5.0 mg/l per calendar day and shall not be less than 4.0 mg/l at any time.	No Standard
	REC	No Standard.	No Standard
	AG	No Standard.	No Standard
Illinois		Not less than 6.0 mg/l during at least 16 hours of any 24-hour period, nor less than 5.0 mg/l at any time.	(Not Applicable)

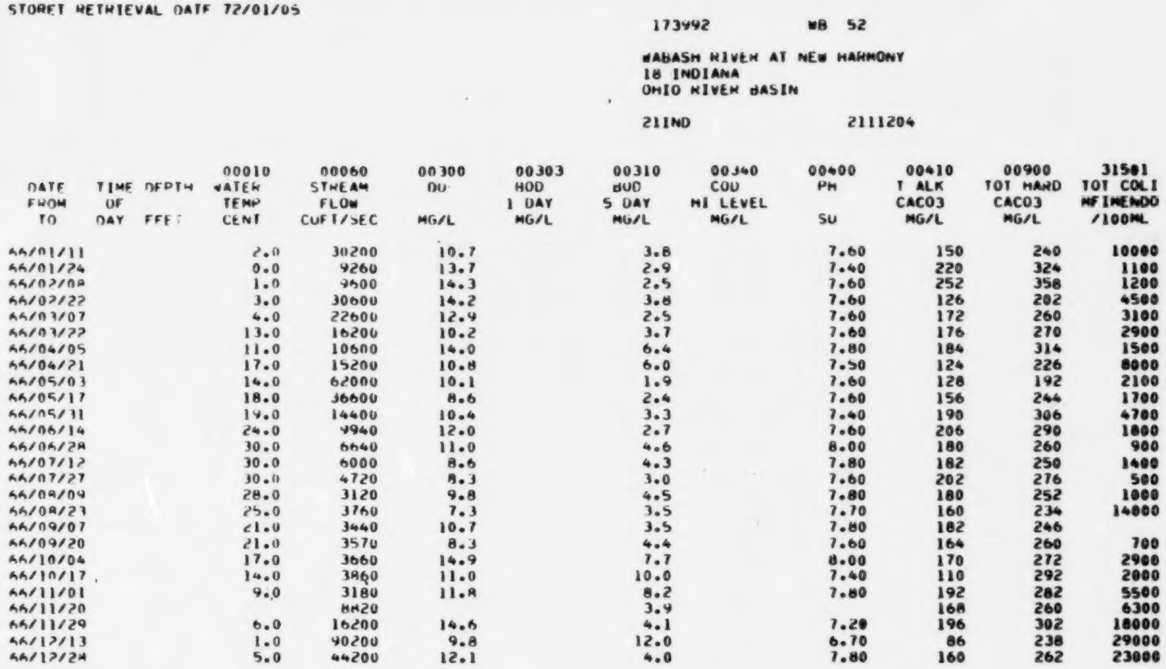
KEY:

PWS – Public Water Supply
IWS – Industrial Water Supply
AL – Aquatic Life
REC – Recreation
AG – Agriculture



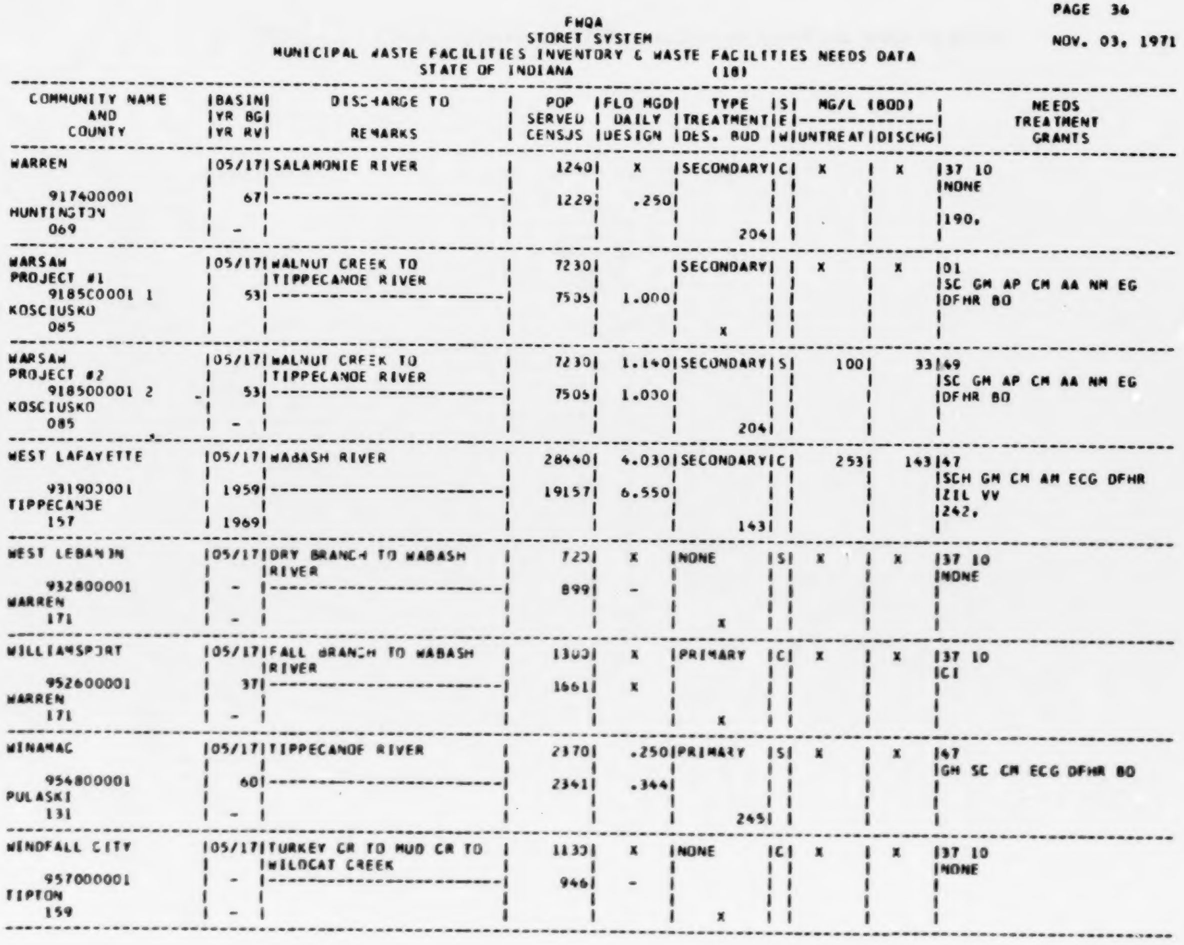
```
STORET  DATE 71/11/05
                                                            173943

                                                            TIPPECANOE RIVER AT OSWEGO
                                                            18 INDIANA
                                                            OHIO RIVER BASIN
                                                            WABASH RIVER BASIN
                                                            11140100            02111204

INDEX 1021500  0C7720  02410  4990
MILES 0953.80 0133.10 311.60 163.05
PARAMETER                                  NUMBER    MEAN   VARIANCE STAN DEV COEF VAR STAND ER  MAXIMUM   MINIMUM  BEG DATE END DATE
00010  WATER      TEMP       CENT              12  22.6250   35.6420  5.97010  .263872  1.72342  27.0000  5.00000 66/03/02 66/09/02
00020   AIR       TEMP       CENT              11  25.2727   18.7691  4.33234  .171423  1.30625  33.0000  20.0000 66/06/27 66/09/02
00060  STREAM     FLOW     CUFT/SEC            11  14.2182   22.0417  4.69486  .330201  1.41555  20.0000  7.80000 66/06/27 66/09/02
00065  STREAM     STAGE      FEET              12  81.5983   567.244  23.8169  .291880  6.87534  88.5500  5.97000 66/03/02 66/09/02
00070   TURB      JKSN        JU                7  25.0000   .000000  .000000           .000000  25.0000  25.0000 66/06/27 66/09/02
00080  COLOR     PT-CO      UNITS               2  22.5000   12.5000  3.53553  .157135  2.50000  25.0000  20.0000 66/06/30 66/09/01
00095 CNDUCTVY   AT 25C    MICROMHO            12  400.416   4275.09  65.3842  .163290  18.8748  490.000  270.000 66/03/02 66/09/02
00300    DO                  MG/L              12  7.80832   10.7390  3.27704  .419686  .946001  14.8000  4.70000 66/03/02 66/09/02
00310   BOD      5 DAY       MG/L               5  2.70000   1.79500  1.33977  .608989  .599166  4.20000  .700000 66/06/28 66/09/02
00340   COD     HI LEVEL     MG/L               3  43.4000   166.682  12.9105  .297478  7.45389  56.0000  30.2000 66/06/28 66/09/01
00400    PH                   SU               12  7.70833   .106268  .325987  .042290  .094104  8.30000  7.20000 66/03/02 66/09/02
00410  T ALK      CACO3      MG/L              12  140.667   1633.70  40.4191  .287340  11.6680  194.000  36.0000 66/03/02 66/09/02
00435 T ACDITY   CACO3       MG/L               5  7.20000   21.7001  4.65833  .646991  2.08327  15.0000  4.00000 66/03/02 66/09/01
00500 RESIDUE    TOTAL       MG/L               2  250.000   2312.00  48.0833  .192333  34.0000  284.000  216.000 66/06/30 66/09/01
00515 RESIDUE   DISS-105   C   MG/L             2  247.500   2244.50  47.3762  .191419  33.5000  281.000  214.000 56/06/30 66/09/01
00530 RESIDUE   TOT NFLT     MG/L               2  2.50000   .500000  .707107  .282843  .500000  3.00000  2.00000 66/06/30 66/09/01
00605  ORG N        N        MG/L               2  .575000   .211250  .459620  .799339  .325000  .900000  .250000 66/06/30 66/09/01
00610 AMMONIA    NH3-N       MG/L               2  .225000   .101250  .318198  1.41421  .225000  .450000  .000000 66/06/30 66/09/01
00620 NITRATE    NO3-N       MG/L               2  .325000   .061250  .247487  .761500  .175000  .500000  .150000 66/06/30 66/09/01
00665  PHOS-T    P-WET       MG/L               2  .150000   .012800  .113137  .754247  .080000  .230000  .070000 66/06/30 66/09/01
00666  PHOS-D    P-WET       MG/L               2  .085000   .000650  .021213  .249566  .015000  .100000  .070000 66/06/30 66/09/01
00900 TOT HARD   CACO3       MG/L               6  223.667   176.687  13.2924  .059429  5.42659  242.000  208.000 66/03/02 66/09/01
00915 CALCIUM   CA,DISS      MG/L               5  57.5999   129.288  11.3705  .197404  5.08504  73.6000  43.2000 66/06/27 66/09/01
00925 MGNSIUM   MG,DISS      MG/L               5  22.0400   88.6129  9.41344  .427107  4.20952  37.1000  11.6000 66/06/27 66/09/01
00940 CHLORIDE     CL        MG/L              12  19.7083   44.2940  6.65538  .337693  1.92124  34.5000  10.0000 66/03/02 66/09/02
00945 SULFATE     SO4        MG/L               2  43.0000   50.0000  7.07107  .164443  5.00000  48.0000  38.0000 66/06/29 66/07/01
00950 FLUORIDE  F,DISS       MG/L               1  .100000                                       .100000  .100000 66/09/01 66/09/01
01045   IRON     TOTAL       UG/L               3  76.6667   11433.3  106.927  1.39470  61.7342  200.000  10.0000 66/07/01 66/09/02
31501 TOT COLI  MFIMENDO    /100ML              8  671.250    389555  624.144  .929823  220.668  2000.00  200.000 66/06/27 66/08/31
31616 FEC COLI  MFM-FCBR    /100ML              4  90.0000   19800.0  140.712  1.56347  70.3562  300.000  10.0000 66/06/28 66/08/31
31679 FECSTREP  MF M-ENT    /100ML              4  55.0000   1633.33  40.4145  .734809  20.2073  110.000  20.0000 66/06/28 66/08/31
38260   MBAS                 MG/L               2  .035000   .001250  .035355  1.01015  .025000  .060000  .010000 66/06/30 66/09/0
```

Figure 13. Typical STORET Summary Data Retrieval for Wabash Basin



```
STORET RETRIEVAL DATE 72/01/05
                                                     173992          WB  52

                                                     WABASH RIVER AT NEW HARMONY
                                                     18 INDIANA
                                                     OHIO RIVER BASIN

                                                     21IND                  2111204

                        00010    00060    00300    00303    00310    00340      00400    00410     00900     31501
  DATE    TIME DEPTH    WATER    STREAM    DO      BOD      BOD       COD       PH      T ALK    TOT HARD  TOT COLI
  FROM     OF           TEMP      FLOW             1 DAY    5 DAY   HI LEVEL            CACO3     CACO3    MFIMENDO
   TO     DAY   FEET    CENT    CUFT/SEC   MG/L    MG/L     MG/L      MG/L       SU      MG/L      MG/L     /100ML

66/01/11                  2.0    30200     10.7              3.8                7.60      150       240     10000
66/01/24                  0.0     9260     13.7              2.9                7.40      220       324      1100
66/02/08                  1.0     9600     14.3              2.5                7.60      252       358      1200
66/02/22                  3.0    30600     14.2              3.8                7.60      126       202      4500
66/03/07                  4.0    22600     12.9              2.5                7.60      172       260      3100
66/03/22                 13.0    16200     10.2              3.7                7.60      176       270      2900
66/04/05                 11.0    10600     14.0              6.4                7.80      184       314      1500
66/04/21                 17.0    15200     10.8              6.0                7.50      124       226      8000
66/05/03                 14.0    62000     10.1              1.9                7.60      128       192      2100
66/05/17                 18.0    36600      8.6              2.4                7.60      156       244      1700
66/05/31                 19.0    14400     10.4              3.3                7.40      190       306      4700
66/06/14                 24.0     9940     12.0              2.7                7.60      206       290      1800
66/06/28                 30.0     6640     11.0              4.6                8.00      180       260       900
66/07/12                 30.0     6000      8.6              4.3                7.80      182       250      1400
66/07/27                 30.0     4720      8.3              3.0                7.60      202       276       500
66/08/09                 28.0     3120      9.8              4.5                7.80      180       252      1000
66/08/23                 25.0     3760      7.3              3.5                7.70      160       234     14000
66/09/07                 21.0     3440     10.7              3.5                7.80      182       246
66/09/20                 21.0     3570      8.3              4.4                7.60      164       260       700
66/10/04                 17.0     3660     14.9              7.7                8.00      170       272      2900
66/10/17                 14.0     3860     11.0             10.0                7.40      110       292      2000
66/11/01                  9.0     3180     11.8              8.2                7.80      192       282      5500
66/11/20                          8820                       3.9                          168       260      6300
66/11/29                  6.0    16200     14.6              4.1                7.20      196       302     18000
66/12/13                  1.0    90200      9.8             12.0                6.70       86       238     29000
66/12/28                  5.0    44200     12.1              4.0                7.80      160       262     23000
```

Figure 14. Typical STORET Data List Retrieval for Wabash Basin



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                                                                                              PAGE  36
                                 FWQA
                             STORET SYSTEM                                                    NOV. 03, 1971
        MUNICIPAL WASTE FACILITIES INVENTORY & WASTE FACILITIES NEEDS DATA
                       STATE OF INDIANA                   (18)
--------------------------------------------------------------------------------------------------------------
 COMMUNITY NAME   |BASIN|      DISCHARGE TO       |  POP  |FLO MGD|   TYPE   |S| MG/L (BOD)    |    NEEDS
      AND         |YR BG|                         |SERVED | DAILY |TREATMENT |E|---------------|  TREATMENT
     COUNTY       |YR RV|         REMARKS         |CENSUS |DESIGN |DES. BOD  |W|UNTREAT |DISCHG|   GRANTS
--------------------------------------------------------------------------------------------------------------
WARREN            |05/17|SALAMONIE RIVER          |   1240|   X   |SECONDARY |C|   X    |  X   |37 10
                  |     |                         |       |       |          | |        |      |NONE
    917400001     |   67|-------------------------|   1229|   .250|          | |        |      |
HUNTINGTON        |     |                         |       |       |          | |        |      |190.
    069           |  -  |                         |       |       |       204| |        |      |
--------------------------------------------------------------------------------------------------------------
WARSAW            |05/17|WALNUT CREEK TO          |   7230|       |SECONDARY | |   X    |  X   |01
PROJECT #1        |     |TIPPECANOE RIVER         |       |       |          | |        |      |SC GM AP CM AA NM EG
    918500001 1   |   53|-------------------------|   7505|  1.000|          | |        |      |DFHR BO
KOSCIUSKO         |     |                         |       |       |          | |        |      |
    085           |     |                         |       |       |    X     | |        |      |
--------------------------------------------------------------------------------------------------------------
WARSAW            |05/17|WALNUT CREEK TO          |   7230|  1.140|SECONDARY |S|     100|    33|49
PROJECT #2        |     |TIPPECANOE RIVER         |       |       |          | |        |      |SC GM AP CM AA NM EG
    918500001 2   |   53|-------------------------|   7505|  1.030|          | |        |      |DFHR BO
KOSCIUSKO         |     |                         |       |       |          | |        |      |
    085           |  -  |                         |       |       |       204| |        |      |
--------------------------------------------------------------------------------------------------------------
WEST LAFAYETTE    |05/17|WABASH RIVER             |  28440|  4.030|SECONDARY |C|     253|   143|47
                  |     |                         |       |       |          | |        |      |SCH GM CM AM ECG DFHR
    931900001     | 1959|-------------------------|  19157|  6.550|          | |        |      |ZIL VV
TIPPECANOE        |     |                         |       |       |          | |        |      |242.
    157           | 1969|                         |       |       |       143| |        |      |
--------------------------------------------------------------------------------------------------------------
WEST LEBANON      |05/17|DRY BRANCH TO WABASH     |    720|   X   |NONE      |S|   X    |  X   |37 10
                  |     |RIVER                    |       |       |          | |        |      |NONE
    932800001     |  -  |-------------------------|    899|   -   |          | |        |      |
WARREN            |     |                         |       |       |          | |        |      |
    171           |  -  |                         |       |       |    X     | |        |      |
--------------------------------------------------------------------------------------------------------------
WILLIAMSPORT      |05/17|FALL BRANCH TO WABASH    |   1300|   X   |PRIMARY   |C|   X    |  X   |37 10
                  |     |RIVER                    |       |       |          | |        |      |CI
    952600001     |   37|-------------------------|   1661|   X   |          | |        |      |
WARREN            |     |                         |       |       |          | |        |      |
    171           |  -  |                         |       |       |    X     | |        |      |
--------------------------------------------------------------------------------------------------------------
WINAMAC           |05/17|TIPPECANOE RIVER         |   2370|   .250|PRIMARY   |S|   X    |  X   |47
                  |     |                         |       |       |          | |        |      |GM SC CM ECG DFHR BO
    954800001     |   60|-------------------------|   2341|   .344|          | |        |      |
PULASKI           |     |                         |       |       |          | |        |      |
    131           |  -  |                         |       |       |       245| |        |      |
--------------------------------------------------------------------------------------------------------------
WINDFALL CITY     |05/17|TURKEY CR TO MUD CR TO   |   1130|   X   |NONE      |C|   X    |  X   |37 10
                  |     |WILDCAT CREEK            |       |       |          | |        |      |NONE
    957000001     |  -  |-------------------------|    946|   -   |          | |        |      |
TIPTON            |     |                         |       |       |          | |        |      |
    159           |  -  |                         |       |       |    X     | |        |      |
--------------------------------------------------------------------------------------------------------------
```

Figure 15. Typical STORET Municipal Wastewater Inventory for Wabash Basin

```
RUN DATE:  NOV. 03, 1971      I N D U S T R I A L    I M P L E M E N T A T I O N    D A T A
                                                    ***INDUSTRIAL IMPLEMENTATION ---1971 UPDATE
                              *****I_1990751          ****    THESE NINE CHARACTERS MUST BE PUNCHED
                                                 IN COLUMNS 1 THRU 9 FOR E V E R Y CARD FROM THIS PAGE.
REGION NUMBER                 (4)...................... 00 - '
STATE NUMBER                  (19)..................... 01 - - '
CITY NUMBER                   (20750).................. 02 - - - - - '
INDUSTRY SERIAL NO.           (90751).................. 03 - - - - - '
COUNTY NUMBER                 (169).................... 04 - - - '
MAJ/MIN/SUB BASIN             (0517  )................. 05 - - - - - - '
COMMUNITY NAME-PART 1.        (WABASH                 ). 06 - - - - - - - - - - - - - - - - - - - - - - - - '
COMMUNITY NAME-PART 2.        (                       ). 07 - - - - - - - - - - - - - - - - - - - - - - - - '
COUNTY NAME                   (WABASH          )....... 08 - - - - - - - - - - - - - - - - - - - - - - - - '
RECEIVING WATERS-PART 1.(WABASH RIVER                 ). 09 - - - - - - - - - - - - - - - - - - - '
RECEIVING WATERS-PART 2.(                             ). 10 - - - - - - - - - - - - - - - - - - - - - - - - '
INDUSTRY NAME - PART 1.  (CONTAINER CORP OF            ). 11 - - - - - - - - - - - - - - - - - - - - - - - - '
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FACILITY REQUIRED  3.    (    )...................... 17 - - - '      .S.I.C.(2).(    ). 39 - - - - ' .
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            C. MM/YY/S  (12691)...................... 22 - - - - - '
            D. MM/YY/S  (12702)...................... 23 - - - - - '
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            B. MM/YY/S  (      )..................... 25 - - - - - '
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LONGITUDE               (           )............... 54 - - - - - - - - '
STATE ORIGINATED CODE   (             )............. 55 - - - - - - - - - - '
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Figure 16. Typical Industrial Implementation Data for Wabash Basin

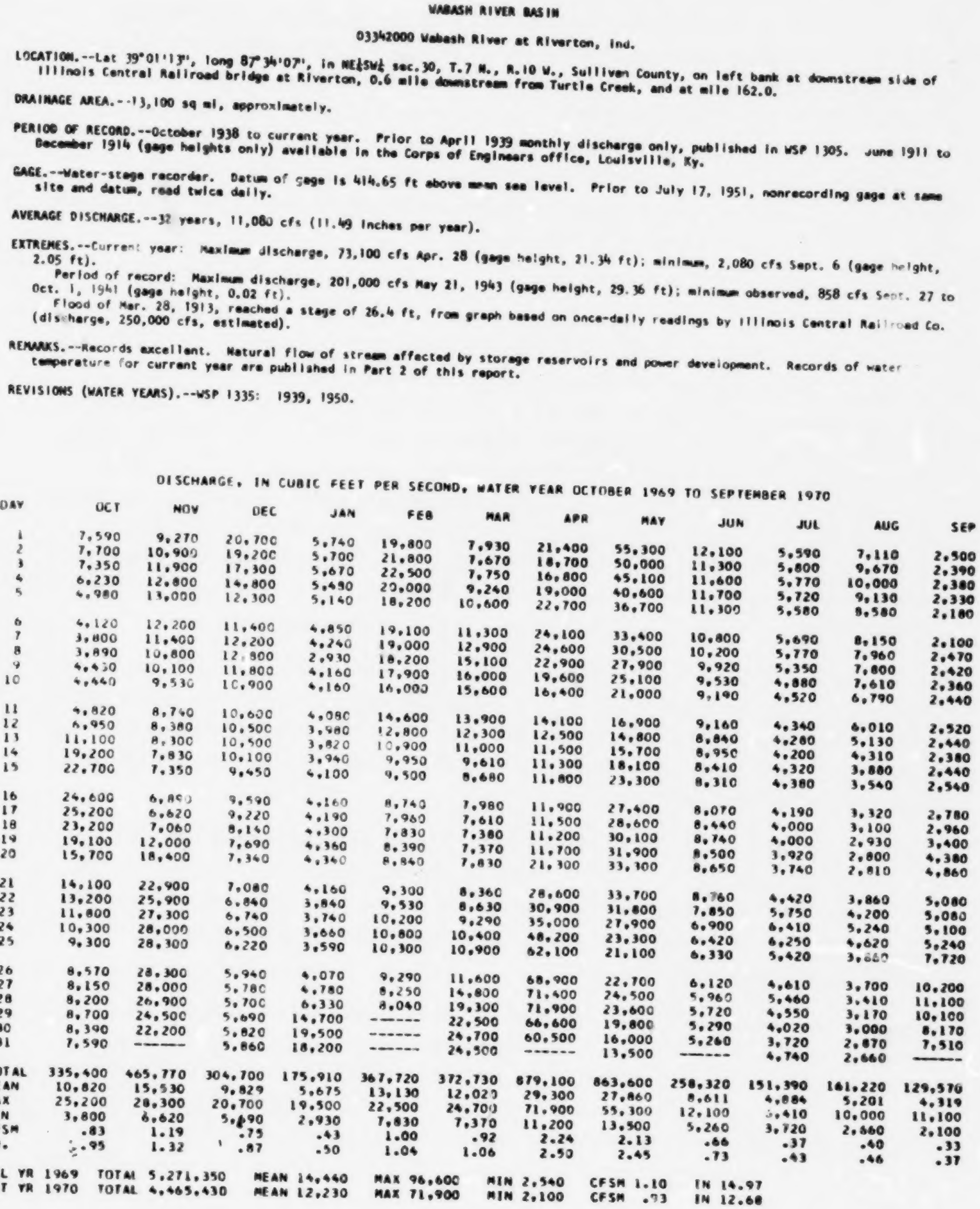
for Illinois," and "Water Resource Data for Ohio" [35, 36, 37]. These documents include daily stream flow data for each of the stations in the Wabash Basin, in a format typified by Figure 17. The USGS also supplied copies of the detailed data sheets on stream flow cross-sections (USGS Form 9-207), as shown in Figure 18. Additional data were provided by direct access to data files of the Indiana Stream Pollution Control Board and the Illinois Environmental Protection Agency, and by an advance copy of Appendix F to the "Wabash River Basin Comprehensive Study" prepared by the Lower Ohio Basin Office of the EPA [38].

Charts and maps of the Wabash Basin are available from the USGS, the U. S. Army Corps of Engineers, and state sources. The Corps of Engineers charts are navigation charts and cover the Wabash River from the mouth to Huntington, Indiana, the White River, and the Eel River. Such navigation charts are extremely useful, since river mileage, bottom contours, and river grade are included. The EPA Water Quality Surveillance Section provided aperture cards of the USGS 15' topographic maps of the basin. Printed copies of the USGS 1:250,000 scale maps of the basin proved extremely useful in gaining an overview of the basin. Other sources of basin maps include the basin maps supplied by the USGS Office of Water Data Coordination with their "Catalog of Information on Water Data—Index to Water Quality Section" [39] and the Rand McNally Road Maps [40], both extremely useful in locating stations.

The so-called "Basin Subset," those streams in the river basin to be included in the monitoring network, is specified to be the Wabash mainstem and Wildcat Creek. The basin subset is mapped in Figure 19. Several tributaries of Wildcat Creek are not included in the basin subset, because no significant effluent sources were located on the tributaries.

A system duration of two months, specifically August and September, was selected. The data on the Wabash indicate few problems on the river during most of the year. During the low flow period of the year (August and September), the number of problem areas increases, requiring abatement-type monitoring at that time.

The water quality parameters selected for system design consideration were BOD-DO for both streams and fluorides on the Wildcat. BOD-DO is representative of the nonconservative, coupled parameters, is a parameter of great interest in water quality evaluation and has a generally high level of data. Fluorides are representative of the conservative class of parameters, has a moderate level of data available for Wildcat Creek, and appears to constitute a potential problem in the creek. The STORET data indicate observed values in excess of the NTE standard for public water supply use.



WABASH RIVER BASIN

03342000 Wabash River at Riverton, Ind.

LOCATION.--Lat 39°01'13", long 87°34'07", in NE¼SW¼ sec.30, T.7 N., R.10 W., Sullivan County, on left bank at downstream side of Illinois Central Railroad bridge at Riverton, 0.6 mile downstream from Turtle Creek, and at mile 162.0.

DRAINAGE AREA.--13,100 sq mi, approximately.

PERIOD OF RECORD.--October 1938 to current year. Prior to April 1939 monthly discharge only, published in WSP 1305. June 1911 to December 1914 (gage heights only) available in the Corps of Engineers office, Louisville, Ky.

GAGE.--Water-stage recorder. Datum of gage is 414.65 ft above mean sea level. Prior to July 17, 1951, nonrecording gage at same site and datum, read twice daily.

AVERAGE DISCHARGE.--32 years, 11,080 cfs (11.49 inches per year).

EXTREMES.--Current year: Maximum discharge, 73,100 cfs Apr. 28 (gage height, 21.34 ft); minimum, 2,080 cfs Sept. 6 (gage height, 2.05 ft).

Period of record: Maximum discharge, 201,000 cfs May 21, 1943 (gage height, 29.36 ft); minimum observed, 858 cfs Sept. 27 to Oct. 1, 1941 (gage height, 0.02 ft).

Flood of Mar. 28, 1913, reached a stage of 26.4 ft, from graph based on once-daily readings by Illinois Central Railroad Co. (discharge, 250,000 cfs, estimated).

REMARKS.--Records excellent. Natural flow of stream affected by storage reservoirs and power development. Records of water temperature for current year are published in Part 2 of this report.

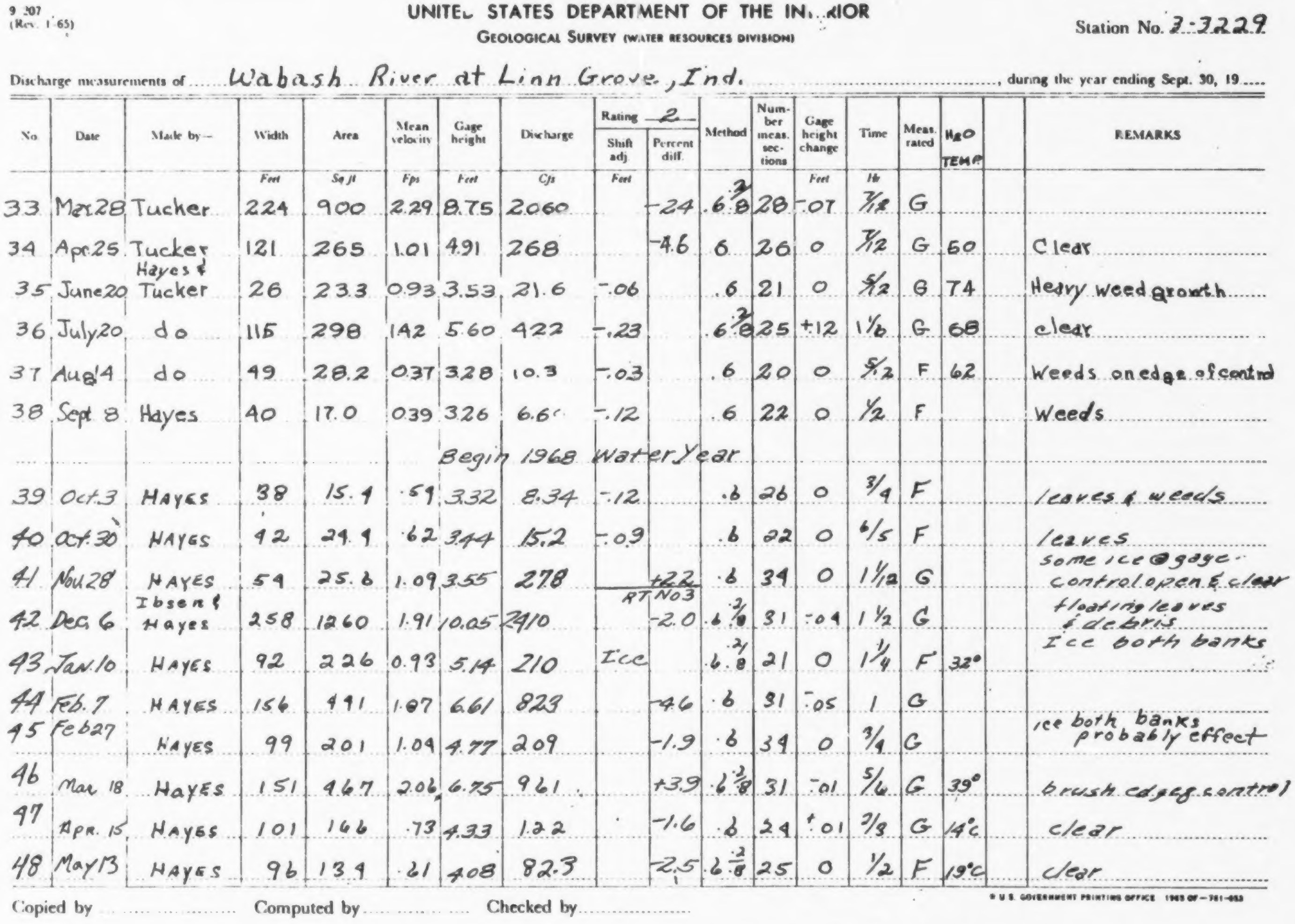
REVISIONS (WATER YEARS).--WSP 1335: 1939, 1950.

DISCHARGE, IN CUBIC FEET PER SECOND, WATER YEAR OCTOBER 1969 TO SEPTEMBER 1970

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	7,590	9,270	20,700	5,740	19,800	7,930	21,400	55,300	12,100	5,590	7,110	2,500
2	7,700	10,900	19,200	5,700	21,800	7,670	18,700	50,000	11,300	5,800	9,670	2,390
3	7,350	11,900	17,300	5,670	22,500	7,750	16,800	45,100	11,600	5,770	10,000	2,380
4	6,230	12,800	14,800	5,490	20,000	9,240	19,000	40,600	11,700	5,720	9,130	2,330
5	4,980	13,000	12,300	5,140	18,200	10,600	22,700	36,700	11,300	5,580	8,580	2,180
6	4,120	12,200	11,400	4,850	19,100	11,300	24,100	33,400	10,800	5,690	8,150	2,100
7	3,800	11,400	12,200	4,240	19,000	12,900	24,600	30,500	10,200	5,770	7,960	2,470
8	3,890	10,800	12,800	2,930	18,200	15,100	22,900	27,900	9,920	5,350	7,800	2,420
9	4,430	10,100	11,800	4,160	17,900	16,000	19,600	25,100	9,530	4,880	7,610	2,360
10	4,440	9,530	10,900	4,160	16,000	15,600	16,400	21,000	9,190	4,520	6,790	2,440
11	4,820	8,740	10,600	4,080	14,600	13,900	14,100	16,900	9,160	4,340	6,010	2,520
12	6,950	8,380	10,500	3,980	12,800	12,300	12,500	14,800	8,840	4,280	5,130	2,440
13	11,100	8,300	10,500	3,820	10,900	11,000	11,500	15,700	8,950	4,200	4,310	2,380
14	19,200	7,830	10,100	3,940	9,950	9,610	11,300	18,100	8,410	4,320	3,880	2,440
15	22,700	7,350	9,450	4,100	9,500	8,680	11,800	23,300	8,310	4,380	3,540	2,540
16	24,600	6,890	9,590	4,160	8,740	7,980	11,900	27,400	8,070	4,190	3,320	2,780
17	25,200	6,620	9,220	4,190	7,960	7,610	11,500	28,600	8,440	4,000	3,100	2,960
18	23,200	7,060	8,140	4,300	7,830	7,380	11,200	30,100	8,740	4,000	2,930	3,400
19	19,100	12,000	7,690	4,360	8,390	7,370	11,700	31,900	8,500	3,920	2,800	4,380
20	15,700	18,400	7,340	4,340	8,840	7,830	21,300	33,300	8,650	3,740	2,810	4,860
21	14,100	22,900	7,080	4,160	9,300	8,360	28,600	33,700	8,760	4,420	3,860	5,080
22	13,200	25,900	6,840	3,840	9,530	8,630	30,900	31,800	7,850	5,750	4,200	5,080
23	11,800	27,300	6,740	3,740	10,200	9,290	35,000	27,900	6,900	6,410	5,240	5,100
24	10,300	28,000	6,500	3,660	10,800	10,400	48,200	23,300	6,420	6,250	4,620	5,240
25	9,300	28,300	6,220	3,590	10,300	10,900	62,100	21,100	6,330	5,420	3,660	7,720
26	8,570	28,300	5,940	4,070	9,290	11,600	68,900	22,700	6,120	4,610	3,700	10,200
27	8,150	28,000	5,780	4,780	8,250	14,800	71,400	24,500	5,960	5,460	3,410	11,100
28	8,200	26,900	5,700	6,330	8,040	19,300	71,900	23,600	5,720	4,550	3,170	10,100
29	8,700	24,500	5,690	14,700	------	22,500	66,600	19,800	5,290	4,020	3,000	8,170
30	8,390	22,200	5,820	19,500	------	24,700	60,500	16,000	5,260	3,720	2,870	7,510
31	7,590	------	5,860	18,200	------	24,500	------	13,500	------	4,740	2,660	------
TOTAL	335,400	465,770	304,700	175,910	367,720	372,730	879,100	863,600	258,320	151,390	161,220	129,570
MEAN	10,820	15,530	9,829	5,675	13,130	12,020	29,300	27,860	8,611	4,884	5,201	4,319
MAX	25,200	28,300	20,700	19,500	22,500	24,700	71,900	55,300	12,100	6,410	10,000	11,100
MIN	3,800	6,620	5,690	2,930	7,830	7,370	11,200	13,500	5,260	3,720	2,660	2,100
CFSM	.83	1.19	.75	.43	1.00	.92	2.24	2.13	.66	.37	.40	.33
IN.	.95	1.32	.87	.50	1.04	1.06	2.50	2.45	.73	.43	.46	.37

CAL YR 1969 TOTAL 5,271,350 MEAN 14,440 MAX 96,600 MIN 2,540 CFSM 1.10 IN 14.97
WAT YR 1970 TOTAL 4,465,430 MEAN 12,230 MAX 71,900 MIN 2,100 CFSM .93 IN 12.68

Figure 17. Typical USGS Stream Flow Data (from [35])



9 207
(Rev. 1-65)

UNITEL STATES DEPARTMENT OF THE IN. RIOR
GEOLOGICAL SURVEY (WATER RESOURCES DIVISION)

Station No. 3-3229

Discharge measurements of Wabash River at Linn Grove, Ind., during the year ending Sept. 30, 19....

No	Date	Made by—	Width	Area	Mean velocity	Gage height	Discharge	Rating 2		Method	Number meas. sections	Gage height change	Time	Meas. rated	H₂O TEMP		REMARKS
								Shift adj	Percent diff								
			Feet	Sq ft	Fps	Feet	Cfs	Feet				Feet	Hr				
33	Mar28	Tucker	224	900	2.29	8.75	2060		-24	.6 .2/.8	28	-.07	7/12	G			
34	Apr25	Tucker	121	265	1.01	4.91	268		-4.6	6	26	0	7/12	G	60		Clear
35	June20	Hayes & Tucker	26	23.3	0.93	3.53	21.6	-.06		.6	21	0	5/12	G	74		Heavy weed growth
36	July20	do	115	298	142	5.60	422	-.23		.6 .2/.8	25	+.12	1 1/6	G	68		clear
37	Aug14	do	49	28.2	0.37	3.28	10.3	-.03		.6	20	0	5/12	F	62		Weeds on edge of control
38	Sept 8	Hayes	40	17.0	0.39	3.26	6.6	-.12		.6	22	0	1/2	F			Weeds
						Begin	1968	Water Year									
39	Oct.3	HAYES	38	15.4	.59	3.32	8.34	-.12		.6	26	0	3/4	F			leaves & weeds
40	Oct.30	HAYES	42	24.4	.62	3.44	15.2	-.09		.6	22	0	6/5	F			leaves
41	Nov.28	HAYES	54	25.6	1.09	3.55	278		+22	.6	34	0	1 1/12	G			some ice @ gage - control open & clear
42	Dec. 6	Ibsen & Hayes	258	1260	1.91	10.05	2410	RT No3	-2.0	.6 .2/.8	31	-.04	1 1/2	G			floating leaves & debris
43	Jan.10	HAYES	92	226	0.93	5.14	210	Ice		.6 .2/.8	21	0	1 1/4	F	32°		Ice both banks
44	Feb.7	HAYES	156	491	1.07	6.61	823		-4.6	.6	31	-.05	1	G			
45	Feb27	HAYES	99	201	1.04	4.77	209		-1.9	.6	34	0	3/4	G			ice both banks probably effect
46	Mar 18	HAYES	151	467	2.06	6.75	961		+3.9	.6 .2/.8	31	-.01	5/6	G	39°		brush edge of control
47	Apr. 15	HAYES	101	166	.73	4.33	122		-1.6	.6	24	+.01	2/3	G	14°c		clear
48	May13	HAYES	96	134	.61	4.08	82.3		-2.5	.6 .2/.8	25	0	1/2	F	19°c		clear

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Figure 18. Typical USGS Stream Gauge Calibration Data Sheet for Wabash Basin

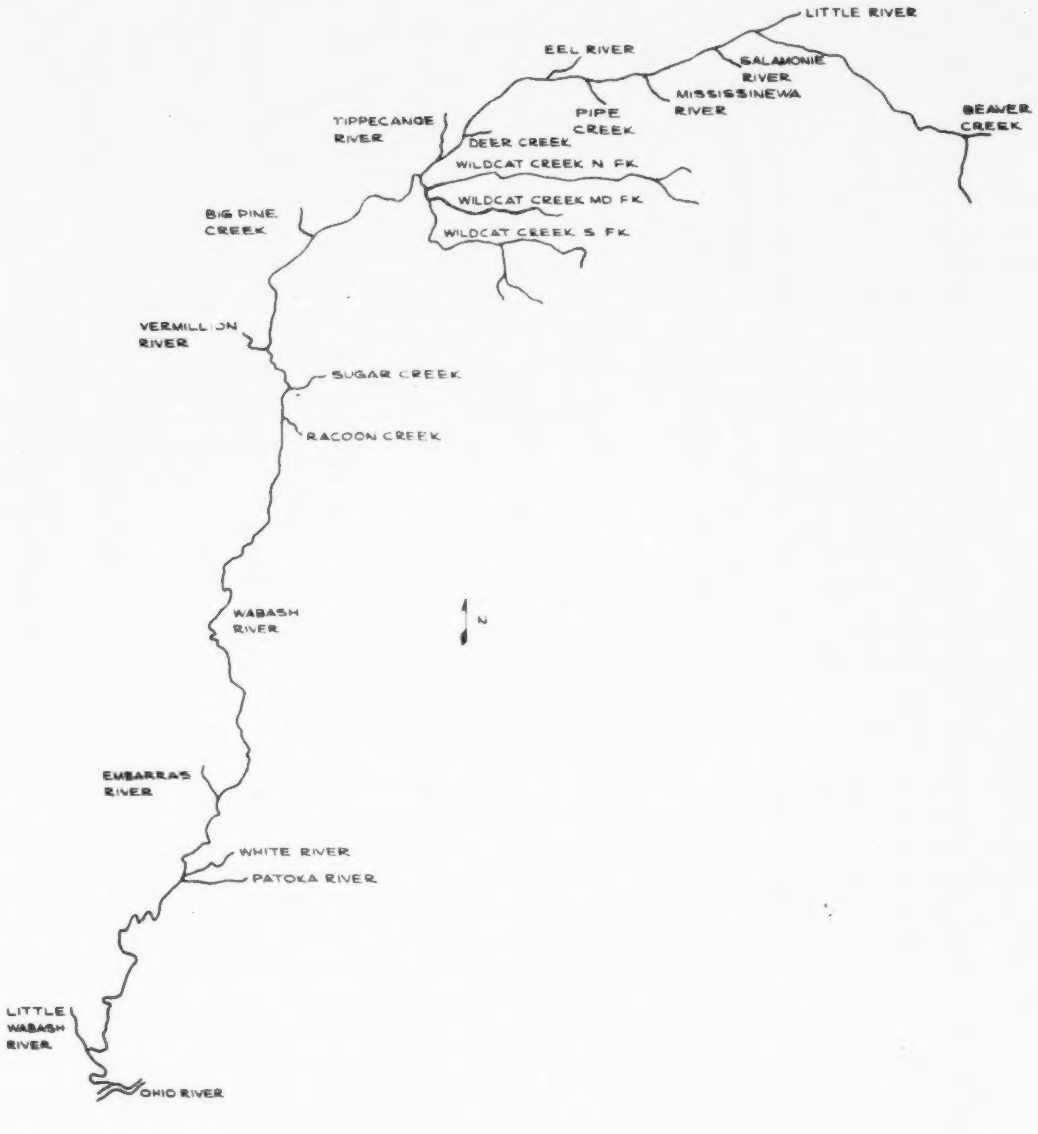

Figure 19. Basin Subset and Major Tributaries

Task Two Activities

During Task Two, the system designer is concerned with conditioning the data collected in Task One for use in later tasks.

Stream flow data from USGS stream gauging stations on the basin subset were analyzed for arithmetic mean values over the system duration. The resultant information is summarized in Table 2.

The major tributaries (in the context of system design) were identified using the arbitrary standard described in Activity 2 of this task. Table 3 presents a tabulation of the major tributaries, with the associated river miles and average flow added to the Wabash over the system duration. Most of the flows used to identify major tributaries were computed directly from USGS stream gauge data. In a few cases, the values were estimates based on drainage area. Table 4 contains a similar tabulation of tributaries to Wildcat Creek.

Much of the data developed during the remaining activities of Task Two eventually find their way onto the computation table assembled during stream segmetation (Task Three).

In preference to duplicating these data in several intermediate tables, they are presented once in the computation tables (Tables 5, 6, and 7). The effluent flow rates derived from Activity 3 of this task are listed there as the Q's, along with a characterization of each source. Similarly, the concentrations of BOD, DO and fluorides in the discharges are tabulated concentrations.

The background parameter concentrations due to distributed sources were estimated through an examination of the historical water quality records, since direct information was not available. For BOD-DO, a background DO deficit of 1 mg/liter was used as representative of BOD runoff. This value is at a moderate level, as indicated in Table G-2, of Appendix G.

The background value for fluorides was set at 0.1 mg/liter, based on inspection of historical data from relatively unaffected parts of Wildcat Creek and its tributaries.

The BOD data for tributaries found in the computation tables are adjusted from 5-day BOD values to ultimate BOD load through multiplication by 1.21. This is based on the BOD decay relationship:

$$L_{5\text{-day}} = L_0 e^{-k_d \text{ (5 days)}} = 0.826\ L_0 \qquad (28)$$

when k_d is taken as 0.35 day^{-1} (a typical value for lab BOD analysis) [41]. Equation (28) is then solved for ultimate BOD (L_0):

Table 2. Stream Flow Data During System Duration in Wabash Basin Subset

Position	Average Depth (ft)	Average Flow Velocity (ft/sec)	Stream Flow (liters/sec)	Temperature (° C)
Wabash River				
New Corydon, Ind.	0.5	0.9	193	23
Linn Grove, Ind.	0.35	0.5	198	23
Huntington, Ind.	0.7	0.97	334	23
Wabash, Ind.	0.80	1.10	1,981	23
Peru, Ind.	1.0	0.90	5,099	22
Logansport, Ind.	1.3	0.76	10,312	21
Delphi, Ind.	1.6	1.7	15,015	22
Lafayette, Ind.	2.5	1.10	36,829	23
Covington, Ind.	3.1	1.25	46,745	23
Montezuma, Ind.	10.1	0.57	57,510	22
Terre Haute, Ind.	6.3	0.74	75,641	22
Riverton, Ind.	3.3	1.55	67,992	23
Vincennes, Ind.	4.0	1.3	73,658	25
Mt. Carmel, Ind.	8.2	0.75	151,565	27
Wildcat Creek and Tributaries				
Jerome, Ind.	0.48	0.25	180	24
Kokomo, Ind.	1.05	0.90	785	30
Owasco, Ind.	1.10	1.50	1,100	22
(South Fork) near Lafayette	0.90	0.50	650	20
Lafayette, Ind.	1.40	0.90	1,950	21

Table 3. Major Tributaries to the Wabash River

Tributary Name	Wabash River Mile	Stream Flow (liters/sec)
Beaver Creek	468	85
Little River	406	261
Salamonie River	394	737
Mississenewa River	375	850
Pipe Creek	363	198
Eel River	354	3,966
Deer Creek	329	850
Tippecanoe River	322	9,066
Wildcat Creek	317	2,266
Big Pine Creek	288	623
Vermillion River	257	1,841
Sugar Creek	245	1,700
Racoon Creek	238	1,445
Embarras River	122	1,983
White River	96	56,660
Patoka River	93	1,417
Little Wabash River	15	850

Table 4. Major Tributaries on the Wildcat Creek Basin

Tributaries to Wildcat Creek	Wildcat Creek River Mile	Stream Flow (liters/sec)
Mud Creek	81	70
Kokomo Creek	64	20
Honey Creek	53	25
South Fork Wildcat Creek	7.5	760
Tributaries to South Fork of Wildcat Creek	**South Fork Wildcat Creek River Mile**	**Stream Flow (liters/sec)**
Prarie Creek	36	150
Kilmore Creek	29	180
Middle Fork Wildcat Creek	3.9	170

$$L_0 = 1.21\ L_{5\text{-day}} \qquad (29)$$

There is only one reservoir in the basin subset on Wildcat Creek approximately 70 river miles above the Wabash. Since the quantitative methods are restricted to use in situations which may be represented as one-dimensional, the reservoir must be excluded from consideration in the system design. A STORET station at river mile 69.8 on the Wildcat was used to estimate the quality of water flowing into the Wildcat below the reservoir.

Task Three Activities

The results of source grouping and stream segmentation are presented in Tables 5, 6, and 7, and diagrammed in Figures 20 and 21. The segment numbering scheme has been set up to consider Wildcat Creek independently from the Wabash River.

The tolerance lengths, on which source grouping and segmentation is based, vary from fractions of a mile to upwards of 5 miles.

Table 8 lists those sources tributary to the Wabash which were grouped together during the Task Three analysis and which were considered major sources. Each of these groups defines the upstream end of a stream segment in Table 5.

A number of single and grouped discharges into the Wabash were ignored during the preliminary design process. In addition to those so small that they escaped

Seg. No. (N)	Segment Position R.M.I.		x_{tol} (Miles)	Stream Depth (ft.)	Flow Velocity (ft/sec)	Stream Flow (liters/sec)	Water Temp (°C)	DO Sat Conc.	k_a (1/day)	Discharge Characterization Industry—S.I.C. Code Municipal—Treatment Tributary—Tributary Name	Discharge Flow Rates (liters/sec.)	Discharge Concentrations (mg/liter)		k_d (1/day)	Seg. No. (N)
	Upstream End	Downstream End										BOD	DO Deficit		
1	482	469	.49	.5	.4	85	23	8.4	18	1) Industrial—2023 2) Industrial—2015 3) Municipal—Secondary	Q_1= .878 Q_2=8.8 Q_3=9.35	L_1=360 L_2= 72 L_3= 20	D_1=0 D_2=0 D_3=6.4		
											Q_g=19.0	L_g=59.6	D_g=3.15	1.4	1
2	469	456	1.1	.5	.9	193	23	8.4	33	Tributary—Beaver Creek	Q_g=108	L_g=3.14	D_g=4.6	1.4	2
3	456	452	.69	.5	.6	195	23	8.4	24	1) Industrial—2033 2) Municipal—Raw	Q_1=8.78 Q_2=7.37	L_1=120 L_2=320	D_1= .031 D_2=8.4		
											Q_g=16.15	L_g=211	D_g=3.84	1.5	3
4	452	434	.66	.6	.5	228	23	8.4	13	Industrial—2025	Q_g=1.1		D_g=.659	1.3	4
5	434	422	1.29	.7	.6	283	23	8.4	15	1) Industrial—2033 2) Municipal—Secondary	Q_1= 1.76 Q_2=57.1	L_1=432 L_2= 23	D_1= .064 D_2=6.4		
											Q_g=58.9	L_g=35.1	D_g=6.2	.8	5
6	422	406	1.20	.7	.6	310	25	8.1	15	1) Industrial—2033 2) Municipal—Secondary	Q_1=8.78 Q_2=4.8	L_1=72 L_2=98	D_1= .119 D_2=6.1		
											Q_g=13.58	L_g=81.1	D_g=2.63	.85	6
7	406	394	1.03	.7	.6	765	25	8.1	15	Tributary—Little River	Q_g=312	L_g=4.57	D_g=1.2	1.0	7
8	394	387	1.72	.8	1.0	1600	24	8.25	16	1) Tributary—Salamonie River 2) Industrial—3275	Q_1=425 Q_2= 6.5	L_1=8 L_2=1900	D_1= 2.5 D_2= .036		
											Q_g=431.5	L_g=35.0	D_g=2.46	1.0	8
9	387	375	1.72	1.0	.9	2050	24	8.25	13	1) Industrial—2631 2) Municipal—Secondary	Q_1= 66 Q_2=121	L_1=100 L_2= 21	.413 6.25		
											Q_g=187	L_g=48.8	D_g=4.19	.9	9
10	375	372	1.79	1.0	.9	4683	23	8.4	11	Tributary—Mississinewa	Q_g=1233	L_g=4.59	D_g=2.35	.9	10
11	372	363	2.46	1.2	.8	4884	23	8.4	7	1) Industrial—Railroad 2) Industrial—2011 3) Municipal—Secondary	Q_1= 1.33 Q_2= .878 Q_3=93	L_1=320 L_2=180 L_3= 5	D_1= .370 D_2= .370 D_3=6.4		
											Q_g=95.2	L_g=11.0	D_g=6.26	.56	11

Table 5. Segmentation Computation Table for Wabash River (Sheet 1 of 3)

Seg. No. (N)	Segment Position R. M. I.		x_{tol} (Miles)	Stream Depth (ft.)	Flow Velocity (ft/sec)	Stream Flow (liters/sec)	Water Temp (°C)	DO Sat Conc.	k_a (1/day)	Discharge Characterization Industry—S.I.C. Code Municipal—Treatment Tributary—Tributary Name	Discharge Flow Rates (liters/sec.)	Discharge Concentrations (mg/liter)		k_d (1/day)	Seg. No. (N)
	Upstream End	Downstream End										BOD	DO Deficit		
12	363	354	1.60	1.3	.75	5,200	23	8.4	5	Tributary—Pipe Creek	Q_g=230	L_g=.60	D_g=2.9	.60	12
13	354	329	2.20	1.4	.90	10,200	22	8.6	6	1) Tributary—Eel River 2) Industrial—3241 3) Industrial—2015 4) Municipal—Secondary	Q_1=4670 Q_2= 1.1 Q_3= .9 Q_4=131	L_1= 1.25 L_2= 24 L_3=120 L_4= 36	D_1=2.4 D_2= .382 D_3= .382 D_4=6.6		
											Q_g=4803	L_g=2.77	D_g=2.51	.70	13
14	329	322	4.30	1.80	1.20	13,500	23	8.4	5	1) Municipal—Secondary 2) Tributary—Deer Creek	Q_1= 20.7 Q_2=450	L_1=40 L_2= 2.1	D_1=6.4 D_2=2.2		
											Q_g=471	L_g=4.05	D_g=2.38	.48	14
15	322	317	3.70	2.50	1.10	22,570	23	8.4	2.2	Tributary—Tippecanoe River	Q_g=9,066	L_g=2.1	D_g=2.0	.51	15
16	317	312	1.78	2.50	1.10	24,840	23	8.4	2.2	Tributary—Wildcat Creek	Q_g=2,266	L_g=1.3	D_g=.1	.50	16
17	312	287	1.04	2.80	1.20	25,782	24	8.25	2.1	1) Industrial—2631 2) Industrial—3352 3) Industrial—3611 4) Industrial—2831 5) Municipal—Secondary 6) Municipal—Secondary	Q_1= 39.5 Q_2= 17.3 Q_3= 83.5 Q_4=254.7 Q_5=180. Q_6=346.9	L_1=120 L_2= 5.6 L_3= 1.6 L_4=475.9 L_5=140.8 L_6= 45.6	D_1= .385 D_2= .385 D_3= .385 D_4= .385 D_5=6.25 D_6=6.25		
											Q_g=942	L_g=177.8	D_g=3.64	.50	17
18	287	271	5.30	3.0	1.20	26,053	24	8.25	2.0	1) Tributary—Big Pine 2) Industrial—3321 3) Municipal—Secondary 4) Municipal—Primary	Q_1=212.5 Q_2= 50.0 Q_3= 2.6 Q_4= 5.9	L_1=3.4 L_2=5.3 L_3=1460 L_4=213	D_1=1.1 D_2=1.064 D_3=6.25 D_4=6.25		
											Q_g=271	L_g=22.6	D_g=1.41	.39	18
19	271	257	3.58	4.0	1.00	27,200	24	8.25	1.2	1) Industrial—2821 2) Municipal—Raw	Q_1=166.9 Q_2= 13.7	L_1= 50 L_2=116	D_1= .705 D_2=6.25		
											Q_g=181	L_g=54.4	D_g=1.27	.48	19
20	257	245	1.15	5.0	.75	29,175	24	8.25	.9	Tributary—Vermillion River	Q_g=1975	L_g=4.65	D_g=3.2	.41	20
21	245	239	2.87	8.0	.60	30,800	24	8.25	.4	Tributary—Sugar Creek	Q_g=990	L_g=4.3	D_g=.7	.36	21
22	239	230	2.63	9.0	.55	34,800	24	8.25	.39	1) Municipal—Raw 2) Tributary—Little Racoon Creek 3) Tributary—Racoon Creek	Q_1=4.39 Q_2=311 Q_3=1445	L_1=163 L_2= 3.95 L_3=2.3	D_1=6.25 D_2=0 D_3=0		
											Q_g=1760	L_g=3.0	D_g=.02	.36	22
23	230	214	3.25	7.0	.68	34,920	24	8.25	.43	Municipal—Primary	Q_g=17.6	L_g=1320	D_g=6.25	.38	23

Table 5. Segmentation Computation Table for Wabash River (Sheet 2 of 3)

Seg. No. (N)	Segment Position R. M. I.		x_{tol} (Miles)	Stream Depth (ft.)	Flow Velocity (ft/sec)	Stream Flow (liters/sec)	Water Temp (°C)	DO Sat Conc.	k_a (1/day)	Discharge Characterization Industry—S.I.C. Code Municipal—Treatment Tributary—Tributary Name	Discharge Flow Rates (liters/sec.)	Discharge Concentrations (mg/liter)		k_d (1/day)	Seg. No. (N)
	Upstream End	Downstream End										BOD	DO Deficit		
24	214	196	3.25	6.3	.73	36,307	25	8.1	.42	1) Municipal—Primary	Q_1=549	L_1=121	D_1=6.1		
										2) Industrial—3352	Q_2= 4.8	L_2= 11	D_2=1.05		
										3) Industrial—2833	Q_3= 69	L_3= 14	D_3=1.05		
										4) Industrial—2871	Q_4= 76	L_4= 6.9	D_4=1.05		
										5) Industrial—2851	Q_5=285	L_5= 85	D_5=1.05		
										6) Industrial—2815	Q_6= 1.8	L_6=180	D_6=1.05		
										7) Industrial—2011	Q_7= 3.3	L_7= 72	D_7=1.05		
										8) Industrial—2631	Q_8=316.	L_8=136	D_8=1.05		
										Grouped Totals	Q_g=1237	L_g=109.4	D_g=3.29	.40	24
25	196	172	3.33	6.0	.80	36,331	25	8.1	.57	1) Municipal—Secondary	Q_1= 9.7	L_1=32.8	D_1=6.0		
										2) Industrial—2871	Q_2=14.0	L_2=94	D_2=2.25		
										Grouped Totals	Q_g=23.7	L_g=69.1	D_g=37.8	.39	25
26	172	158	1.97	4.5	.80	37,000	25	8.1	1.0	Municipal—Primary	Q_g=3.9	L_g=177	D_g=6.1	.39	
27	158	128	2.48	3.8	.65	38,120	25	8.1	1.1	1) Municipal—Secondary	Q_1=41.6	L_1= 23	D_1=6.1		
										2) Industrial—7503	Q_2=50.0	L_2=101	D_2=1.0		
										3) Industrial—3400	Q_3= 2.6	L_3= 26	D_3=1.0		
										4) Municipal—Secondary	Q_4= 4.4	L_4= 73.2	D_4=6.1		
										Grouped Totals	Q_g=98.6	L_g=65.6	D_g=3.33	.45	26
28	128	122	2.99	3.5	.80	41,600	26	8.0	1.2	1) Municipal—Primary	Q_1= 94	L_1=106	D_1=6.0		
										2) Industrial—2611	Q_2=119	L_2= 80	D_2= .229		
										Grouped Totals	Q_g=213	L_g=91.3	D_g=2.78	.46	27
29	122	115	3.15	6.0	.75	43,583	25	8.1	.61	Tributary—Embarras River	Q_g=1709	L_g=3.4	D_g=1.6	.41	28
30	115	95	4.9	7.2	.60	44,500	25	8.1	.47	1) Municipal—Secondary	Q_1=5.8	L_1=87.2	D_1=6.1		
										2) Municipal—Primary	Q_2=5.3	L_2=149	D_2=6.1		
											Q_g=11.1	L_g=117.	D_g=6.1	.31	29
31	95	89	3.25	8.2	.70	98,705	25	8.1	.40	1) Tributary—White River	Q_1=42,500	L_1=2.44	D_1=1.43		
										2) Industrial—2661	Q_2= 19	L_2=3181	D_2= .573		
										3) Municipal—Primary	Q_3= 53	L_3=102	D_3=6.1		
										4) Tributary—Patoka River	Q_4=1133	L_4=8.4	D_4=2.7		
											Q_g=43,705	L_g=3.99	D_g=1.47	.37	30
32	89	65	5.7	8.7	.70	98,749	24	8.25	.40	Municipal—Secondary	Q_g=44	L_g=40	D_g=6.25	.21	31
33	65	0	3.22	8.2	.70	98,819	24	8.25	.40	1) Tributary—Bonpas Creek	Q_1=57	L_1=3.14	D_1= .423		
										2) Municipal—Primary	Q_2=13	L_2=147	D_2=6.25		
											Q_g=70	L_g=30.2	D_g=1.51	.37	32

Table 5. Segmentation Computation Table for Wabash River (Sheet 3 of 3)

Seg. No. (N)	Segment Position R. M. I.		x_{tol} (Miles)	Stream Depth (ft.)	Flow Velocity (ft/sec)	Stream Flow (liters/sec)	Water Temp (°C)	DO Sat. Conc.	k_a (1/day)	Discharge Characterization Industry—S. I. C. Code Municipal—Treatment Tributary—Tributary Name	Discharge Flow Rates (liters/sec.)	Discharge Concentrations (mg/liter)		k_d (1/day)	Seg. No. (N)
	Upstream End	Downstream End										BOD	DO Deficit		
1A	90	86	.22	.40	.20	21.7	25	8.1	24	Municipal—Raw	$Q_g=7.5$	$L_g=30$	$D_g=8.1$	1.6	1A
1B	86	81		.40	.20	70.0	24	8.25	24	Tributaries—Mud and Irwin Creeks				1.6	1B
1C	81	76		.48	.25	180.	24	8.25	19	Tributaries				1.4	1C
2	76	74	1.06	.60	.40	270	26	8.0	12	Municipal—Secondary				.65	2
3	74	70		Reservoir—Not Included in Procedure											3
4	70	64	1.23	.50	.50	400	26	8.0	14	Reservoir	$Q_g=380$	$L_g=0$	$D_g=3.2$	.70	4
5	64	53	1.55	1.05	.90	785	30	7.5	6	1) Industrial—3315 2) Industrial—3361 3) Industrial—2573 4) Municipal—Secondary	$Q_1=172$ $Q_2=14.5$ $Q_3=0.4$ $Q_4=598$	$L_1=3.7$ $L_2=7.3$ $L_3=4.0$ $L_4=40.0$	$D_1=0$ $D_2=0$ $D_3=0$ $D_4=5.5$		
											$Q_g=785$	$L_g=31.4$	$D_g=4.19$	1.0	5
6	Honey 5	Creek 0	.43	.40	.20	15	23	8.4	24	Municipal—Secondary	$Q_g=7.02$	$L_g=112$	$D_g=6.4$	.8	6
7A	53	27	2.21	.85	.90	830	23	8.4	7	Tributary—Honey Creek	$Q_g=25$	$L_g=9.45$	$D_g=3.53$	.7	7A
7B	27	7.5		1.2	1.0	1100	23	8.4	4	Tributaries				.6	7B
	South Fork, Wildcat Creek														
8	46	36	.22	.40	.20	25	20	9.0	24	Municipal—Raw	$Q_g=3.01$	$L_g=320$	$D_g=9.0$	1.6	8
9A	36	29	.74	.50	.30	190	20	9.0	13	Tributary—Prairie Creek	$Q_g=150$	$L_g=20$	$D_g=5.0$	.7	9A
9B	29	24.2		.70	.50	390	20	9.0	11	Tributary—Kilmore Creek					9B
10A	24.2	3.9	.78	.90	.50	550	20	9.0	8	Municipal—Raw	$Q_g=7.0$	$L_g=320$	$D_g=9.0$	1.1	10A
10B	3.9	0	1.72	1.0	.60	760	20	9.0	9	Tributary—Middle Fork, Wildcat Creek	$Q_g=170$	$L_g=.41$	$D_g=.023$	.6	10B
11	Middle Fork, Wildcat Creek 16	0	.74	.50	.30	170	19	9.2	13	Municipal—Secondary	$Q_g=6.15$	$L_g=110$	$D_g=7.2$	.7	11
7C	7.5	0	3.10	1.4	.90	1950	21	8.85	3	Tributary—South Fork, Wildcat Creek	$Q_g=760$	$L_g=.34$	$D_g=.025$	.5	7C

Table 6. Segmentation Computation Table for Wildcat Creek—BOD-DO

Seg. No. (N)	Segment Position R. M. I.		x_{tol} (Miles)	Stream Depth (ft.)	Flow Velocity (ft/sec)	Stream Flow (liters/sec)	Water Temp (°C)	DO Sat. Conc.	k_a (1/day)	Discharge Characterization Industry—S. I. C. Code Municipal—Treatment Tributary—Tributary Name	Discharge Flow Rates (liters/sec.)	Discharge Concentrations (Fluorides)	k_d (1/day)	Seg. No. (N)
	Upstream End	Downstream End												
1A	90	86	.22	.40	.20	21.7	25	8.1	24	Municipal—Raw	Q_g=7.5	C_g (fl) = 1.0	0	1A
1B	86	81		.40	.20	70.0	24	8.25	24	Tributaries—Mud and Irwin Creeks			0	1B
1C	81	76		.48	.25	180.	24	8.25	19	Tributaries			0	1C
2	76	74	1.06	.60	.40	270	26	8.0	12	Municipal—Secondary		C_g (fl) = 1.0	0	2
3	74	70		Reservoir—Not Included in Procedure										3
4	70	64	1.23	.50	.50	400	26	8.0	14	Reservoir	Q_g=380	C_g (fl) = .153	0	4
5	64	53	1.55	1.05	.90	785	30	7.5	6	1) Industrial—3315 2) Industrial—3361 3) Industrial—2573 4) Municipal—Secondary	Q_1=172 Q_2= 14.5 Q_3= 0.4 Q_4=598			
											Q_g=785	C_g (fl) = 1.4	0	5
6	Honey 5	Creek 0	.43	.40	.20	15	23	8.4	24	Municipal—Secondary	Q_g=7.02	C_g (fl) = 1.0	0	6
7A	53	27	2.21	.85	.30	830	23	8.4	7	Tributary—Honey Creek	Q_g=25	C_g (fl) = .57	0	7A
7B	27	7.5		1.2	1.0	1100	23	8.4	4	Tributaries			0	7B
	South Fork, Wildcat Creek													
8	46	36	.22	.40	.20	25	20	9.0	24	Municipal—Raw	Q_g=3.01	C_g (fl) = 1.0	0	8
9A	36	29	.74	.50	.30	190	20	9.0	13	Tributary—Prairie Creek	Q_g=150	C_g (fl) = 1.2	0	9A
9B	29	24.2		.70	.50	390	20	9.0	11	Tributary—Kilmore Creek			0	9B
10A	24.2	3.9	.78	.90	.50	550	20	9.0	8	Municipal—Raw	Q_g=7.0	C_g (fl) = 1.0	0	10A
10B	3.9	0	1.72	1.0	.60	760	20	9.0	9	Tributary—Middle Fork, Wildcat Creek	Q_g=170	C_g (fl) = .13	0	10B
11	Middle Fork, Wildcat Creek 16	0	.74	.50	.30	170	19	9.2	13	Municipal—Secondary	Q_g=6.15	C_g (fl) = 1.0	0	11
7C	7.5	0	3.10	1.4	.90	1950	21	8.85	3	Tributary—South Fork, Wildcat Creek	Q_g=760	C_g (fl) = .34	0	7C

Table 7. Segmentation Computation Table for Wildcat Creek—Fluorides

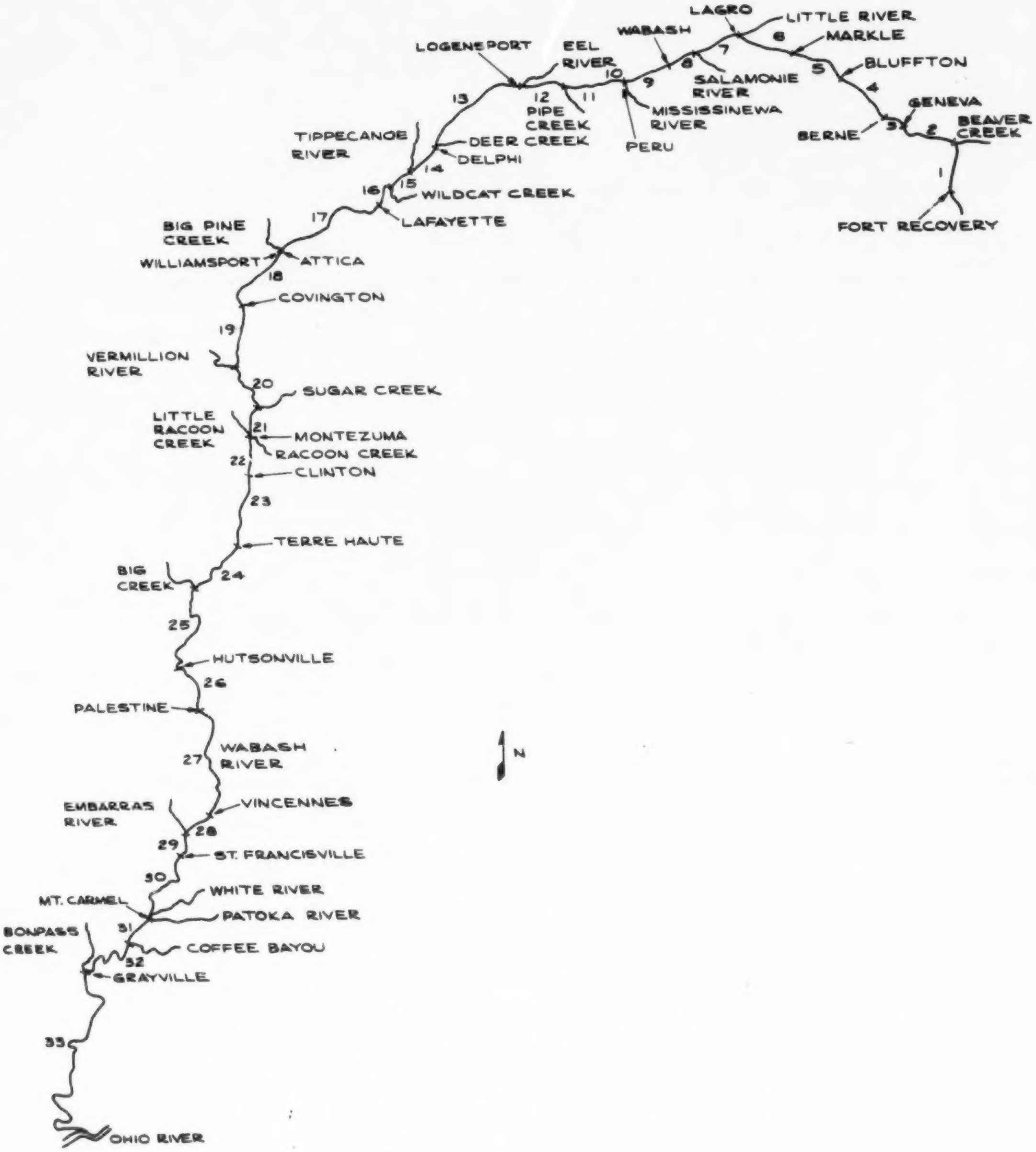

Figure 20. Segmentation of Wabash River

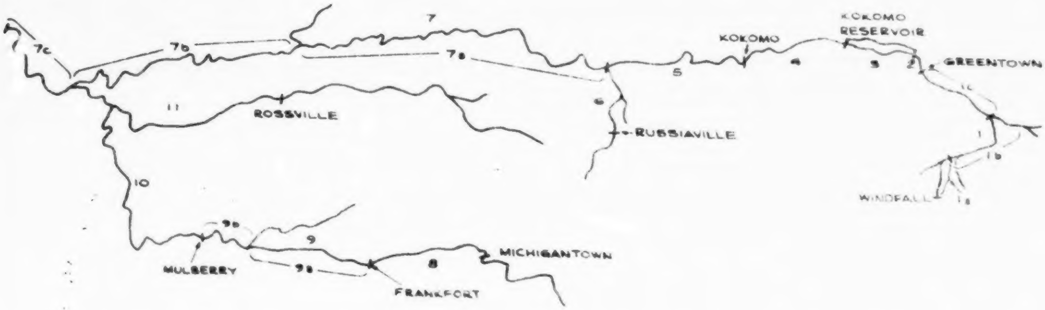

Figure 21. Wildcat Creek and Tributaries in Segmented Form

notice completely, Table 9 presents a tabulation of those sources that were intentionally eliminated from consideration, based on their minimal impact. It should be noted that the Little Wabash River (Q = 850 liter/sec) is eliminated from consideration, while the Mississinewa River (Q = 850 liter/sec) is not. This is due to the relative impact of the two streams. The Mississinewa River enters the Wabash at a point where the total flow is approximately 1/20 of the flow at the confluence of the Little Wabash with the Wabash.

In several cases on Wildcat Creek, segments are determined not by the presence of major pollutant sources, but by significant changes in stream characteristics. These changes are associated with additional flow from relatively "clean" tributaries.

Group characteristics are computed as weighted averages of the individual source loads. For example, the D_g computed for segment 6 in the Wildcat subbasin is:

$$D_g \text{ (segment 6)} = \frac{(0)(172) + (0)(14.5) + (0)(0.4) + (5.5)(598)}{172 + 14.5 + 0.4 + 598}$$

$$= 4.19 \text{ mg/liter}$$

Tasks Four and Five

The results of stream characterization and rating of segment priorities are presented in Tables 10, 11, and 12.

Table 8. Discharge Points on the Wabash River that are Grouped and Considered Major Sources

Discharge Points	Associated River Mile
Salamonie River—Largo	394
Eel River—Logansport (town)	354
Delphi—Deer Creek	329
Wildcat Creek—Burnetts Creek	317
Big Pin Creek—Attica (town)—Williamsport (town)	287
Montezuma (town)—Little Racoon Creek—Racoon Creek	239
Hutsonville—Turmans Creek	172
St. Francisville—Poker Creek	115
White River—Mount Carmel (town)—Patoka River	95
Bonpass Creek	65

Table 9. Discharges on the Wabash River Ignored Due to Small Impact

Discharge	Associated River Mile
Andrews	401
Rock Creek	341
Little Pine Creek	296
Mill Creek—Little Vermillion River	249
Brouillets Creek	226
Lost Creek	218
Honey Creek	204
Prairie Creek	180
Busseron Creek	142
New Harmony (town)—Black River	51
Little Wabash River	15

Seg. No. (N)	Segment Position R. M. I.		x_F (Miles)	L_0 (mg/l)	D_0 (mg/l)	x_m (Mi.)	D_m (mg/l)	$\overline{C}_m$ (mg/l)	D_F (mg/l)	L_F (mg/l)	σ (mg/l)	C_t (mg/l)	P Priority Rating With No Impl	R Correlations	D_1^* (Impl on Segment) 25	C_1^*	σ_1^*
	Upstream End	Downstream End															
1	482	469	13	10.9	.704	.434	.8	6.54	.057	.68	.9	5	-1.71	0	.8	6.54	-1.71
2	469	456	13	2.43	2.51	0	2.51	4.89	.031	.71	.9	5	.122	.02	2.59	4.89	.122
3	456	452	4	18.2	.345	1.17	.965	6.44	.659	9.9	.9	5	-1.6	.04	.965	6.44	-1.6
4	452	434	18	10.1	.659	[illegible]	.778	6.62	.064	.576	.9	5	-1.8	.98	.778	6.62	-1.8
5	434	422	12	7.77	1.34	0	1.34	6.06	.119	2.11	.9	5	-1.18	.05	1.34	6.06	-1.18
6	422	406	16	6.14	.224	1.34	.310	6.79	.092	1.53	.9	5	-1.99	.37	.310	6.79	-1.99
7	406	394	12	2.48	.527	0	.527	6.57	.036	.73	.9	5	-1.74	.08	.527	6.57	-1.74
8	394	387	7	9.51	.726	0	.726	6.52	.413	6.2	.9	5	-1.69	.01	.726	6.52	-1.69
9	387	375	12	9.4	.805	0	.805	6.45	.322	4.33	.9	5	-1.61	.50	.805	6.45	-1.61
10	375	372	3	6.49	.760	0	.760	6.64	.370	5.40	.9	5	-1.82	.27	.760	6.64	-1.82
11	372	363	9	5.62	.487	0	.487	6.91	.264	3.51	.9	5	-2.12	.73	.487	6.91	-2.12
12	363	354	9	3.68	.390	.182	.405	6.99	.382	2.05	.9	5	-2.21	.61	.405	6.99	-2.21
13	354	329	25	2.40	1.40	0	1.40	6.20	.097	.732	.9	5	-1.33	.12	1.40	6.20	-1.33
14	329	322	7	.878	.198	0	198	7.20	.096	.740	.9	5	-2.44	.47	.198	7.20	-2.44
15	322	317	5	1.29	.861	0	.861	6.54	.594	.748	.9	5	-1.71	.07	.852	6.55	-1.72
16	317	312	5	.80	.55	0	.55	6.85	.385	.695	.9	5	-2.06	.92	.51	6.89	-2.10
17	312	287	25	7.16	.50	14.4	1.19	6.06	1.06	3.66	.9	5	-1.18	.31	1.08	6.17	-1.3
18	287	271	16	3.86	1.07	0	1.07	6.18	.705	2.81	.9	5	-1.31	.99	.770	6.48	-1.64
19	271	257	14	3.17	.71	11.5	.904	6.35	.898	2.26	.9	5	-1.50	.92	.642	6.61	-1.79
20	257	245	12	2.42	1.05	1.28	1.06	6.19	.964	1.62	.9	5	-1.32	.81	.731	6.52	-1.69
21	245	239	6	1.7	.95	6.0	1.05	6.20	1.05	1.36	.9	5	-1.33	.88	.651	6.60	-1.78
22	239	230	9	1.45	.99	6.49	1.03	6.22	1.03	.982	.9	5	-1.36	.98	.577	6.67	-1.86
23	230	214	16	1.65	1.03	7.63	1.08	6.17	1.05	1.45	.9	5	-1.30	.94	.534	6.66	-1.84
24	214	196	18	5.12	1.12	18	2.25	4.85	2.25	2.80	.9	5	.167	.45	.023	7.07	-2.30
25	196	172	24	2.84	2.26	0	2.26	4.84	1.95	1.39	.9	5	.178	.99	Impl*		
26	172	158	14	1.41	1.95	0	1.95	5.15	.926	.973	.9	5	- .17	.99	.020	7.08	-2.31
27	158	128	30	1.15	.932	0	.932	6.17	.221	.322	.9	5	-1.30	.99	.019	7.08	-2.31
28	128	122	6	1.43	.243	6	.405	6.60	.405	1.16	.9	5	-1.78	.52	.198	6.80	-2.00
29	122	115	7	1.25	.605	7	.649	6.45	.649	.989	.9	5	-1.61	.72	.401	6.70	-1.89
30	115	95	20	1.02	.65	1.04	.651	6.45	.573	.504	.9	5	-1.61	.99	.410	6.69	-1.88
31	95	89	6	2.00	.912	6	1.06	6.04	1.06	1.65	.9	5	-1.16	.49	.869	6.23	-1.37
32	89	65	24	1.67	1.07	0	1.07	6.03	.848	1.08	.9	5	-1.17	.95	.888	6.36	-1.51
33	65	0	65	1.10	.849	4.96	.851	6.40	.345	.134	.9	5	-1.56	.98	.706	6.54	-1.71

Table 10. Priority Computation Table for Wabash River

Seg. No. (N)	Segment Position R. M. I.		x_E (Miles)	L_0 (mg/l)	D_0 (mg/l)	x_m (mg/l)	D_m (mg/l)	$\overline{C}_m$ (mg/l)	D_E	L_E	e	C_t	P	R	D_1^*	$\overline{C}_1^*$	P_1^*	D_2^*	$\overline{C}_2^*$	P_2^*
	Upstream End	Downstream End																		
1	90	76	14	110	3.42	.30	6.28	.82	.003	.04	1.2	5	3.46	0	Impl	1	1	1		
2	76	74	2	1.55	.04	1.34	.073	6.93	.071	1.27	1.2	5	-1.61	.073	.068	6.93	-1.61	.068	6.93	-1.61
3		Reservoir																		
4	70	64	6	0	3.2	0	3.2	3.80	0	0	1.2	5	1.00	0	3.2	3.80	1.00	3.2	3.80	1.00
5	64	53	11	31.4	4.19	2.03	4.54	1.96	2.95	14.9	1.8	5	1.69	0	4.54	1.96	1.69	Impl 2	2	
6	5	0	5	52.4	3.53	0	3.53	3.87	.31	9.45	1.2	5	.94	0	3.53	3.87	.94	3.53	3.87	.94
7	53	7.5	45.5	14.7	2.97	0	2.97	4.43	1.12	.297	1.8	5	.32	.96	2.97	4.43	.32	.19	8.21	-2.68
8	46	36	10	38.5	1.08	.32	2.19	5.61	.02	.289	1.2	5	- .66	0	2.19	5.81	- .66	2.19	5.81	- .66
9	36	24.2	7	17.2	4.29	0	4.29	3.71	.065	1.12	2.0	5	.65	.01	4.29	3.71	.65	4.29	3.71	.65
10	24.2	3.9	20.3	6.70	.22	2.08	.696	7.3	.070	.437	2.0	5	-1.15	.17	.696	7.3	-1.15	.696	7.3	-1.15
11	16	0	16	3.98	.26	0	.26	7.94	.023	.41	1.2	5	-2.45	0	.26	7.94	-2.45	.26	7.94	-2.45

Table 11. Priority Computation Table for Wildcat Creek–BOD-DO

Seg. No. (N)	Segment Position R. M. I.		C_0(fl) = C_m(fl)	C_E(fl)	σ	C_t (mg/l)	P	R	C_1^*	P_1^*
	Upstream End	Downstream End								
1	90	76	.65	.14	.3	1	-1.16	0	.60	-1.33
2	76	74	.176	.153	.3	1	-2.75	.80	.16	-2.80
3		Reservoir								
4	70	64	.153	.136	.3	1	-2.82	1.00	.14	-2.87
5	64	53	1.40	1.40	.3	1	1.33	.097	Impl 1 *	1 *
6	5	0	.57	.57	.3	1	-1.43	0	* .57	* -1.43
7	53	7.5	1.37	1.05	.3	1	.17	.98	.03	-3.23
8	46	36	.26	.21	.3	1	-2.63	0	.26	-2.63
9	36	24.2	1.06	.53	.3	1	-1.57	.20	1.06	-1.57
10	24.2	3.9	.54	.42	.3	1	-1.93	.98	.54	-1.93
11	16	0	.13	.13	.3	1	-2.9	0	.13	-2.90

Table 12. Priority Computation Table for Wildcat Creek–Fluorides

The computation of the characteristics of each segment is performed using the grouped source loads found in Tables 5, 6, and 7.

The standard deviations are estimated from historical water quality records. There were insufficient data on the variability of effluent sources to permit use of mathematical models in characterizing parameter variability. In the case of fluorides, the estimate is extremely poor, due to the small number of fluoride observations during the system duration period.

The standard threshold (C_T) used for BOD-DO (5 mg/liter) is the value set by Indiana for use of the waters to support aquatic life. The standard threshold selected for fluorides (1 mg/liter) is the standard for public water supplies and food processing, a use to which the Wildcat is put.

The initial segment priorities (P) computed for BOD-DO range from +0.178 to -2.44 in the Wabash and +3.48 to -2.45 in the Wildcat. Thus, if only priority were considered in establishing surveillance in a segment, the first station in the basin subset should be implemented in the headwaters of the Wildcat, where the priority of 3.48 is found. It should be noted that, over the system duration (the annual low flow period), the priorities in the Wildcat tend to be positive, while those in the Wabash are predominantly negative. This indicates a generally higher probability of violation in the Wildcat than in the Wabash, a situation documented in the STORET data.

In the case of fluorides on the Wildcat, the initial segment priorities are seen to range from +1.33 to -2.9, with the maximum in the segment just below Kokomo (segment 5).

To illustrate several points about the relationship between initial segment priority and ultimate segment priority, three separate cases have been examined.

In the first case, it is assumed of interest to establish a surveillance system to detect DO violations on the Wabash. Considering only priority as a criterion for station implementation, the first station would be in segment 25, below Terre Haute, where the initial segment priority is +0.178. Computation of the ultimate segment priority, based on a station in segment 25, gives the values in the column labeled P_1* (Table 10). It can be seen that the priorities in segments 24 and 26 are radically lowered, while those in segments 15 through 23 and 27 through 33 are somewhat lower. Upstream of segment 15 there is no change, due primarily to the low correlation between segments 14 and 15. (The column labeled R gives the correlation with the upstream segment, R_{ij} for $i = j - 1$.) Following computation of ultimate segment priority, segment 2 has the highest ultimate priority of those remaining (+0.122). This may be compared with the ultimate segment priority of segment 24 (-2.30). The initial segment priority in segment 24 was 0.167, nearly equal to that of segment 25. Thus, consideration of intersegment correlation is an important feature of the system design process.

In the second case, it is assumed of interest to set up a monitoring system for DO on the Wildcat and its tributaries. Using priority as the sole criterion for establishment of surveillance in a segment, the station in the headwaters of the Wildcat would be established first ($P = 3.48$). In this case, the intersegment correlations are predominantly zero, leading to no change in the order of segment priority after computation of P_1*. Similarly, there is no change after implementation of surveillance in segment 5, just below Kokomo. It should be noted that the reason for the initial high priority of the headwaters segment during the system duration is the low stream flow at that point, not the magnitude of the source.

In the final case, a monitoring system for fluorides on the Wildcat and its tributaries is assumed. Comparing this system with that on the Wildcat for BOD-DO, it can be seen that system design based solely on priority considerations can lead to widely differing configurations for different parameters. In the case of fluorides, the first station to be implemented would be in segment 5. After computing ultimate priorities based on that monitoring station, it can be seen that the next station would go in the headwaters of the Wildcat, the first choice in the case of BOD-DO.

Turning to the location of stations in the segments, the column labeled x_m gives the distance of the preferred station location below the upstream segment boundary. Thus, the surveillance station for monitoring DO in segment 25 on the Wabash would be at the upstream end of the segment, river mile 196. It should be noted that any station established to monitor DO in segment 24 would preferrably be 18 miles below its upstream boundary, or river mile 196. This interesting result may be attributed to the interaction of the large impact on the stream at Terre Haute and the slight improvement due to dilution at the downstream segment boundary. In the case of fluorides, the monitoring may be carried out anywhere within the segment, since fluorides are a conservative water quality parameter.

Task Six Activities

The procedure for determining time-sampling ratings was exercised for two cases of interest on the Wabash River. The cases are the two segments with highest ultimate segment priority, segment 25 and segment 2. The design parameter is BOD-DO. Four candidate sampling frequencies are considered: daily, weekly, monthly, and quarterly. The base data are for the period of system duration (August and September) over the years 1961 through 1965.

Table 13 is the computation table for the two demonstration cases. It can be seen that, for some purposes, a weekly sampling rate might be appropriate in segment 25, below Terre Haute, since M is 0.7 under that sampling scheme.

In contrast, a daily sampling rate would be required to obtain a comparable M in the headwaters of the Wabash. A weekly sampling rate at the headwaters yields a very poor M = 0.17. The result is intuitively satisfactory; the volume of flow in segment 2 is 0.2% of the flow in segment 25 and subject to greater variability over short periods of time. A higher frequency of observation should be anticipated under those circumstances. The quantitative procedure provides a numerical measure of precisely how much higher the frequency must be to achieve the same results.

N'	N	$Q_{(n-1)}$	Q_g	C_{sat}	C_m	C_T	D_{bk}	Q_T		ΔQ	T_0	T_1	Δ	M	Δ	M	Δ	M	Δ	M
Implementation Sequence No.	Segment Number	Stream Flow (l/sec)	Effluent Group Flow (l/sec)	Saturation DO Conc. (mg/l)	Maximum DO Cond. (mg/l)	Threshold DO Conc. (mg/l)	Background DO Deficit (mg/l)	Threshold Stream Flow (CFS)	Stream Flow Station	Stream Flow Adjustment (CFS)	Nonviolation Duration (days)	Violation Duration (days)	Sampling Period (days)	Priority Rating	Sampling Period (days)	Priority Rating	Sampling Period (days)	Priority Rating	Sampling Period (days)	Priority Rating
1	25	36307	23.7	8.1	4.84	5.0	1.0	1380	3415	0	46.8	13	1	.96	7	.70	30	.33	90	.10
2	2	85	108	8.4	4.89	5.0	1.0	3.3	3225	0	25.1	1.2	1	.66	7	.17	30	.03	90	<.01
3																				
4																				
5																				
6																				
7																				
8																				
9																				

Table 13. Computation Table for Temporal Priority Rating for Wabash Mainstem

SECTION VIII
DISCUSSION

Having developed a procedure for quantitative preliminary design of water quality surveillance systems and successfully demonstrated it in one case, it is worthwhile to discuss the procedure in the general context of governmental water quality programs.

The procedure has been successfully demonstrated on portions of the Wabash River Basin. Based on this demonstration, it is believed the essential concepts of the procedure are sound. The determination of segment priority provides a realistic measure of need to monitor, with adequate resolution for clear separation of low- and high-need segments. The inclusion of a measure of intersegment correlation provides a clearly useful means of reassessing priority as stations are implemented. The rules for location of stations are consistent with our understanding of river processes and the method of analyzing sampling frequency provides a quantitative assessment of the "goodness" of a given sampling scheme.

The procedures developed here are applicable to the design of surveillance systems that have abatement as their primary objective. Other surveillance objectives include prevention and program control. A method has been developed by Ward [1] to analyze the emphasis of a state's water quality policy with respect to the three surveillance objectives. If that method is applied and abatement is found to be an important objective, then the quantitative procedures developed here provide definitive numerical methods for performing each of Ward's design tasks, up to the point of cost considerations. It is of interest to note that the quantitative procedure described in this report provides an analytical method for evaluating sampling frequency, in contrast to the computer simulation method of Ward[1].

Where comparisons could be made between the two methods, the results indicate general agreement. As sampling interval becomes small (i.e., frequency increases), both methods indicate an asymptotic approach to 100% detection, with fixed pollution event characteristics. Similarly, for fixed sampling interval both indicate approach to 100% detection as the average violation duration approaches the system duration.

That the quantitiative procedures are useful in one demonstration and that the results are similar to those achieved by independent analysis does not constitute proof of generality. The general applicability of the quantitative procedure can only be confirmed by its successful use in a number of river basins. It may be anticipated that such application may locate insufficiencies in the User Handbook and detailed implementation. The recommendations of Section II have suggested a means of dealing with such problems as may be encountered. It is not anticipated that such application will find fault with the overall theoretical structure of the method.

There is some concern that the shear volume of the User Handbook may limit its application by appearing unwieldy, in spite of the fact that every effort has been made to simplify and limit the effort required by the handbook procedure. Realistically, the user must anticipate that application of the method requires the commitment of manpower resources. While the commitment is justified by the resulting minimization of risk in system implementation, the demands on manpower can be substantial. The experience of the Wabash demonstration indicates that the system designer may wish to give careful thought to his work plan before beginning preliminary design activities.

The recommendation to computerize the quantitative design procedure is based on the experience of the demonstration. A major portion of the quantitative procedure is devoted to organizing water quality data and using it in stream characterization. The mathematical models to be used by the EPA in establishing computerized basin models (for example [10]) for planning purposes [42, 43, 44] can provide these data directly. Thus, the laborious stream characterization portion of the quantitative procedure can be eliminated and the remaining portions more rapidly computed.

While it is clear that the quantitative preliminary design procedure permits a useful analysis of the requirements for water quality surveillance, they do not provide a complete tool for design of water quality surveillance systems. Extension of the procedure to include cost and performance factors, as recommended in Section II, will equip the user with a means for evaluating realizable systems against the requirements of preliminary design.

SECTION IX
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SECTION XI

GLOSSARY

TERMINOLOGY

Background Parameter Concentration—The concentration assumed in the stream due to distributed sources.

Basin Subset—That portion of a river basin which is under consideration in preliminary design.

BOD—Biochemical Oxygen Demand.

Design Parameters—Those water quality parameters being considered in the preliminary design.

DO—Dissolved oxygen.

"Macroscopic" Concept—The overview approach to system design which limits the spatial and temporal scales.

NLT—Not less than.

NTE—Not to exceed.

Preliminary Design—That stage of surveillance system design which deals solely with the relationship of the surveillance system to the natural system.

Source Group—A group of effluent outfalls considered as a single source for design purposes.

System Duration—That time over which the water quality surveillance system will maintain a fixed configuration of spatial and temporal sampling.

USGS—United States Geological Survey.

USPHS—United States Public Health Service.

MATHEMATICAL NOTATION

A_1—A function defined by equation (19).

A_2—A function defined by equation (19).

a_k^n—A function defined by equation (29).

b_k^n—A function defined by equation (29).

C—In general, concentration.

C_0— A function defined by equation (29).

C_1— A function defined by equation (29).

C_m—The expected worse case value of the parameter concentration in the segment.

C_T—The standards threshold in the segment.

C_s—Concentration of parameter at source.

C_{sat}—Saturation concentration of DO.

C_g—Equivalent mean concentration due to a source group.

D—DO deficit concentration.

D_0—Initial DO deficit concentration at upstream end of segment.

D_E—Initial DO deficit concentration at upstream end of segment due to upstream segment.

D_s—Initial DO deficit concentration at upstream end of segment due to source.

E—The mathematical expectation (or expected value).

exp—The exponential function.

e—The exponential function.

f_{0n}—A function defined by equation (29).

f_{1n}—A function defined by equation (29).

f_s—Sampling frequency.

f_N—Nyquist frequency.

G—degradation variable

I—parameter index

k—Decay rate coefficient.

k_d—BOD deoxygenation rate coefficient.

k_a—Reaeration rate coefficient.

L—Concentration of BOD.

L_0—Initial concentration of BOD at upstream end of segment.

L_E—Initial concentration of BOD at upstream end of segment, due to upstream segment.

L_s—Concentration of BOD in source effluent.

ln—The natural logarithm.

M—Priority measure for temporal sampling.

M*—Estimator for M.

N—Segment index.

n_d—Average number of detection pulse strings.

n—Dummy variable of summation.

n_v—Average number of violations.

Pr—Probability.

P—Initial segment priority.

$P_n{}^*$—Ultimate segment priority of a segment resulting from n implementations.

p—Probability density function.

Q—Stream Flow.

Q_E—Stream flow at upstream end of segment due to upstream segment.

Q_s—Flow at upstream end of segment due to source.

Q_0—Stream flow at upstream end of segment.

Q_g—Total flow due to source group.

Q_t—Stream flow threshold.

R_{ij}—Estimator for ρ_{ij}.

R—Relative effect of upstream segment (equation (11).

S—Sampling process, a function of time.

s—Dummy variable of integration.

T_0—Average interval between violations.

T_1—Average duration of violation.

t—Time—an independent variable.

T—A dummy variable of integration.

U—Stream velocity (positive downstream).

v—Magnitude of a water quality parameter (a function of time).

V_0—Threshold value of parameter as defined by standards. (Used in time sampling analysis.

W_s—BOD discharge rate at source.

x—Linear distance from upstream end of a segment (positive downstream).

x_m—Linear distance of minimum (or maximum) parameter value, with respect to upstream end of segment.

x_E—The length of a segment.

x_c—Critical distance; location of minimum in DO sag curve.

y—The violation process, a two-state variable.

y_s—The sampled violation process.

z—A variable defined as $y(t) - y(t - \Delta)$.

z^+—A variable defined as the positive pulses of z.

z_s^+—$z^+(t)\ S\ (t)$.

α—Sufficient statistic for P (equation (C-4)

Δ—The sampling interval.

π_i—Probability that y is in state i at time t, given that it was in state i at time t=0.

π_v—Probability of violation.

π—Ratio of circumference of a circle to its radius.

ρ_{ij}—Cross-correlation between segments i and j.

σ_c—The expected standard deviation of the parameter in the segment.

ψ—Parameter of the Rayleigh distribution.

SECTION XII

APPENDICES

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APPENDIX A

CHARACTERIZATION OF STREAM WATER QUALITY DATA BASE

This appendix reports a review of the water quality data base available for use in preliminary design of water quality surveillance systems. This review substantially corroborates and updates a similar review published by Sayers [3], based on data from 1968.

The objective of the review was the determination of the level of data which the user might typically expect to find in the application of the quantitative design procedure. By determining the level in advance, methods for characterization of the natural system could be developed which accommodated the available data and which contained means for circumventing inadequacies in the data base.

The stream data base is composed of all the historical records of the characteristics of the stream. Some 700 individual descriptors of stream water quality characteristics (parameters) have been identified [5].

A survey of the available data on stream water quality parameters was made by a statistical analysis of a representative sample drawn from the U.S. Geological Survey publication Catalogue of Information on Water Data [39]. This approach was taken, in preference to a direct survey of STORET, to minimize the level of effort required. The USGS Office of Water Data Coordination publication already contained a level of summarization which was not immediately available through STORET. The set of stations described in the USGS publication is not strictly identical to the set of stations in STORET. There is sufficient overlap, however, to conclude that the USGS data set is representative of the STORET stations.

The results of the statistical survey are presented in Tables A-1 through A-19. The statistics contained in these tables represent: 1) the number of stations measuring each parameter at each frequency, 2) the total number of stations measuring each parameter, and 3) the total number of measurements at each frequency. Each of the first 18 tables contains data on 80 stations selected at random in a particular geographical area of the country. The 15 parameters listed are those most pertinent to enforcement of federal-state water quality standards. Table A-19 presents a summary of the preceding tables, for a total of 1440 stations nation-wide (approximately a 3% sample of the STORET inventory of about 45,000 stations, and 6% of the stations reported in the USGS publication).

To summarize the tables in qualitative terms, given a river with several (at least 3) stations on it:

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- Water temperature is measured on at least one station
- There is a 0.9 probability that dissolved solids, common ions, hardness, and pH are measured at least at one point
- Data on turbidity, color, chlorides, nutrients, dissolved oxygen, and coliforms have a high probability (0.7) of availability
- Odor, suspended solids, and radioactive chemical observations are each performed in less than 20% of the stations in the sample
- The dominant frequency of measurement nationwide is monthly, but the frequency of measurement is highly variable from geographical area to geographical area.

A property of the existing data base not portrayed in the tables is the station density. The data base survey indicates that rivers may be grouped into three major categories, according to station density:

- Rivers in or near major metropolitan areas
- Rivers supporting significant, but less than urban, populations
- Creeks and remote streams.

Four major rivers in metropolitan areas were reviewed and the average separation between adjacent stations was computed:

- Maximum observed separation—4.00 miles
- Minimum observed separation—1.23 miles
- Mean observed separation—2.7 miles.

These stations are often located adjacent to or downstream of major outfalls. A survey of 38 streams in Category 2 disclosed the following station separation statistics:

- Maximum observed separation—96.0 miles
- Minimum observed separation—7.1 miles
- Mean observed separation—17.9 miles
- Standard deviation—15.1 miles

Review of streams in Category 3 indicates a very sparse monitoring network. Typically streams of this type have no station at all. When one is located on the stream, it is typically at the mouth.

In conclusion, the user can anticipate having stream water quality data available on the parameters of interest under most circumstances, but the data may be expected to have a low spacial and temporal intensity.

Note

All numbers in Table A-1 through A-19 are taken out of a total of 80 sample stations. For example, there are a total of 60 stations out of 80 in the sample measuring temperature of Table A-1. Twenty-five of them take monthly measurements.

Table A-1. Occurrence of Parameter Measurement and Frequencies in the Northeast (Sample Includes Streams in Connecticut, New Hampshire, Vermont, Maine, and New York)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	60	1	6		1	7	25	19		
Turb.	47	5				4	28	10		
Color	37	7				10	7	11	2	
Odor	12					3	7	2		
pH	23	7					7	9		
Sus. Solids	11						7	2	2	
Dis. Solids	30	10					14	4	2	
Chloride	32	3					17	10	2	
Nutrients (N)	23	2				2	10	9		
Nutrients (P)	14	3					11			
Com. Ions	41	7				2	21	9	2	
Hardness	41	5				1	23	10	2	
Radio Chem.	33	3					1	26	3	
D.O.	17	2	1			1	12	1		
Coliform	45	2			1	8	13	21		
Totals	466	57	7		2	38	203	143	15	

†Frequency Code:

Code	Frequency	Code	Frequency	Code	Frequency
*	Not Periodic	3	Daily	6	Quarterly
1	Continuous	4	Weekly	7	Annually
2	Seasonal	5	Monthly	8	Other Periodic

Table A-2. Occurrence of Parameter Measurement and Frequencies in the Northeast (Sample Includes Streams in New Jersey)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	80	1			7	4	22	36		10
Turb.	62				1	3	22	36		
Color	78	1				1	25	36		15
Odor	62					1	25	36		
pH	78	1			3	1	22	36		15
Sus. Solids	9							9		
Dis. Solids	46	1					3	27		15
Chloride	20	1					3	1		15
Nutrients (N)	78	1				1	25	36		15
Nutrients (P)	50							34		15
Com. Ions	19	1					3			15
Hardness	19	1					3			15
Radio Chem.	27							27		
D.O.	76	1			6	1	22	34		12
Coliform	62				1	3	22	36		
Totals	766	9			18	15	175	384		142

†Frequency Code:
* Not Periodic
1 Continuous
2 Seasonal
3 Daily
4 Weekly
5 Monthly
6 Quarterly
7 Annually
8 Other Periodic

Table A-3. Occurrence of Parameter Measurement and Frequencies in the Northeast (Sample Includes Streams in New York, New Jersey, and Pennsylvania)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	77		13		2	5	15	21		20
Turb.	31		1			2	7	21		
Color	60					2	9	21		26
Odor	21							21		
pH	64				1		14	23		26
Sus. Solids	28						7	21		
Dis. Solids	64					2	12	24		26
Chloride	43						17	2		25
Nutrients (N)	31					2	14	6		9
Nutrients (P)	42						11	22		9
Com. Ions	70	2					18	24		26
Hardness	69					2	18	23		26
Radio Chem.	25	2						21	2	
D.O.	25		4			2	10			9
Coliform	25					2	1	21		1
Totals	675	4	18		3	19	153	271	2	203

†Frequency Code:

- * Not Periodic
- 1 Continuous
- 2 Seasonal
- 3 Daily
- 4 Weekly
- 5 Monthly
- 6 Quarterly
- 7 Annually
- 8 Other Periodic

Table A-4. Occurrence of Parameter Measurement and Frequencies in the Southeast (Sample Includes Streams in North Carolina and South Carolina)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	80		2		21		3	16	35	3
Turb.	20				15				2	3
Color	57				3		1	7	35	11
Odor	1				1					
pH	78				21		1	7	35	14
Sus. Solids	5								2	3
Dis. Solids	57						1	7	35	14
Chloride	21						1	7	1	12
Nutrients (N)	56						2	7	35	12
Nutrients (P)	57						2	7	35	13
Com. Ions	77				19	2	3	5	35	13
Hardness	72				15		1	7	35	14
Radio Chem.	2								2	
D.O.	30						3	5	19	3
Coliform	27				21		3		1	2
Totals	640		2		116	2	21	75	307	117

†Frequency Code:

- * Not Periodic
- 1 Continuous
- 2 Seasonal
- 3 Daily
- 4 Weekly
- 5 Monthly
- 6 Quarterly
- 7 Annually
- 8 Other Periodic

Table A-5. Occurrence of Parameter Measurement and Frequencies in the Southeast (Sample Includes Streams in Florida)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	79		1		4				29	45
Turb.	3								2	1
Color	78	1			1				53	23
Odor										
pH	78	1							53	24
Sus. Solids										
Dis. Solids	77								53	24
Chloride	73								51	22
Nutrients (N)	78								52	26
Nutrients (P)	78	1							51	26
Com. Ions	78	1							53	24
Hardness	76								51	25
Radio Chem.	3	1							2	
D.O.	78	1							66	11
Coliform	2									2
Totals	781	6	1		5				510	253

†Frequency Code:

* Not Periodic
1 Continuous
2 Seasonal
3 Daily
4 Weekly
5 Monthly
6 Quarterly
7 Annually
8 Other Periodic

Table A-6. Occurrence of Parameter Measurement and Frequencies in the Southeast (Sample Includes Streams in Florida and Georgia)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	65		3		3	12	18	8	14	3
Turb.	42		1		1	12	16	8		
Color	53					12	16	8	14	3
Odor										
pH	46				1	12	16		14	3
Sus. Solids	35					12	15	8		
Dis. Solids	53					12	16	8	14	3
Chloride	54		1			12	17	8	13	3
Nutrients (N)	53					12	17	8	13	3
Nutrients (P)	53					12	16	8	14	3
Com. Ions	55				1	12	17	8	14	3
Hardness	53					12	17	8	13	3
Radio Chem.	1									1
D.O.	56		2			12	17	8	11	2
Coliform	50					12	30	8		
Totals	669		7		6	156	228	96	134	30

†Frequency Code:

* Not Periodic	3 Daily	6 Quarterly
1 Continuous	4 Weekly	7 Annually
2 Seasonal	5 Monthly	8 Other Periodic

Table A-7. Occurrence of Parameter Measurement and Frequencies in the Central South (Sample Includes Streams in Alabama and Mississippi)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	79		6	2	14	1	40		7	9
Turb.	27				13	1	6			7
Color	45	1			13	1	18			12
Odor	11	10			1					
pH	70	18			12		28	1		11
Sus. Solids										
Dis. Solids	39				3	1	21	2		12
Chloride	29				2		21	2		4
Nutrients (N)	26				10	1	6	1		8
Nutrients (P)	19				10		1			8
Com. Ions	67	30			2		22	1		12
Hardness	58	29			3	1	14	1		10
Radio Chem.	20	18			1		1			
D.O.	41		1		9	1	22	1		7
Coliform	20	1			10	1	2			6
Totals	551	107	7	2	103	8	202	9	7	106

†Frequency Code:

* Not Periodic	3 Daily	6 Quarterly
1 Continuous	4 Weekly	7 Annually
2 Seasonal	5 Monthly	8 Other Periodic

Table A-8. Occurrence of Parameter Measurement and Frequencies in Kentucky, Indiana, Arkansas, Missouri, Tennessee, and Mississippi

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	56	9			5	5	18	1		16
Turb.	37	2			3	2	6	5		19
Color	35	1				2	7	5	1	19
Odor	21				2		1			18
pH	39	1			1	2	14	2		19
Sus. Solids	9						3	5		1
Dis. Solids	39	3			1	1	8	7		19
Chloride	39				2	2	14	2		19
Nutrients (N)	19	2				1	8	6		2
Nutrients (P)	34	1				1	8	6		18
Com. Ions	42	3			2	3	8	7		19
Hardness	33	11			2	3	8	7		2
Radio Chem.	12	3			1		4	3		1
D.O.	42	3			2	3	15			16
Coliform	39	1			2	2	10	5		19
Totals	496	40			23	27	110	61	1	207

†Frequency Code:

* Not Periodic	3 Daily	6 Quarterly
1 Continuous	4 Weekly	7 Annually
2 Seasonal	5 Monthly	8 Other Periodic

Table A-9. Occurrence of Parameter Measurement and Frequencies in Ohio, Kentucky, West Virginia, and Indiana

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	28	3	5		7	3	7	3		
Turb.	39	1			3	4	6	3		22
Color	40	4				2	8	3	1	22
Odor	28				3			3		22
pH	63				3	2	11	3	22	22
Sus. Solids	6							3		3
Dis. Solids	55				1	2	7	3	22	20
Chloride	63				1	4	10	3	21	24
Nutrients (N)	12					2	4	5		1
Nutrients (P)	31	1	1				2	8		19
Com. Ions	67	2			4	2	12	3	22	22
Hardness	46				3	4	11	3	22	3
Radio Chem.	8	2					1	5		
D.O.	15		3			2	7	3		
Coliform	39	1			2	4	7	3		22
Totals	540	14	9		27	31	93	54	110	202

†Frequency Code:

* Not Periodic	3 Daily	6 Quarterly
1 Continuous	4 Weekly	7 Annually
2 Seasonal	5 Monthly	8 Other Periodic

Table A-10. Occurrence of Parameter Measurement and Frequencies in the Mid East (Sample Includes Streams in Ohio, West Virginia, and Pennsylvania)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	47	1	6	1	5	6	7	21		
Turb.	40	1			10	5	3	21		
Color	22					2	3	17		
Odor	19					2		17		
pH	46				8	5	10	17	6	
Sus. Solids	25						4	21		
Dis. Solids	41					3	11	21	6	
Chloride	37				1	2	14	14	6	
Nutrients (N)	31			1		2	14	14		
Nutrients (P)	33			1			8	24		
Com. Ions	53	2		1	7	6	10	21	6	
Hardness	53				10	10	9	18	6	
Radio Chem.	10	2						8		
D.O.	38		2	1		14	5	16		
Coliform	45				4	8	9	22	2	
Totals	540	6	8	5	45	65	107	272	32	

†Frequency Code:
- * Not Periodic
- 1 Continuous
- 2 Seasonal
- 3 Daily
- 4 Weekly
- 5 Monthly
- 6 Quarterly
- 7 Annually
- 8 Other Periodic

Table A-11. Occurrence of Parameter Measurement and Frequencies in the Mid West (Sample Includes Streams in Minnesota, Wisconsin, and Illinois)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	69	2	21	1			30			15
Turb.	20						5			15
Color	18						18			
Odor	1						1			
pH	41						25			16
Sus. Solids	28						17			11
Dis. Solids	35	2				1	17			15
Chloride	47						19	13		15
Nutrients (N)	53					1	11	16		25
Nutrients (P)	46					1	5	16		24
Com. Ions	27	2				1	6	17		1
Hardness	23	2					15	4		2
Radio Chem.	13						2	10	1	
D.O.	36						18	13		5
Coliform	34						21			13
Totals	491	8	21	1		4	210	89	1	157

†Frequency Code:

* Not Periodic	3 Daily	6 Quarterly
1 Continuous	4 Weekly	7 Annually
2 Seasonal	5 Monthly	8 Other Periodic

Table A-12. Occurrence of Parameter Measurement and Frequencies in the Mid West (Sample Includes Streams in Montana, South Dakota, Minnesota, and Wisconsin)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	75		1		3		67			4
Turb.	45						43			2
Color	63	1			1		48	3	8	2
Odor	35						35			
pH	30	1					18	3	8	
Sus. Solids	37						35			2
Dis. Solids	24	1					12	3	8	
Chloride	62	1					47	3	8	3
Nutrients (N)	44						37	5		2
Nutrients (P)	62	1					43	8	8	2
Com. Ions	59				1		43	3	8	3
Hardness	62	1					48	3	8	
Radio Chem.	43			1			13		27	2
D.O.	50						48			2
Coliform	53					3	48			2
Totals	744	7	1	1	5	3	585	31	83	26

†Frequency
Code:
* Not Periodic
1 Continuous
2 Seasonal
3 Daily
4 Weekly
5 Monthly
6 Quarterly
7 Annually
8 Other Periodic

Table A-13. Occurrence of Parameter Measurement and Frequencies in the Mid West (Sample Includes Streams in Nebraska, Iowa, North Dakota, South Dakota, and Montana)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	59		8	1	8	5	29	5		3
Turb.	23		2	1	1	1	18			
Color	29					2	13	10	1	3
Odor	5				2		3			
pH	36		2	4	3		17	6	1	3
Sus. Solids	3						3			
Dis. Solids	43			4	2	2	25	6	1	3
Chloride	34				1	2	22	6	1	2
Nutrients (N)	41	2	1	5		1	24	5		3
Nutrients (P)	42	2	1	5		1	24	5	1	3
Com. Ions	46			4	3	1	26	6	1	5
Hardness	47		1	5	1	1	30	6	1	2
Radio Chem.	12						8		2	2
D.O.	37			1		3	16	4	8	5
Coliform	25				2	2	16	3		2
Totals	482	4	15	29	23	21	274	62	17	36

†Frequency Code:
* Not Periodic
1 Continuous
2 Seasonal
3 Daily
4 Weekly
5 Monthly
6 Quarterly
7 Annually
8 Other Periodic

Table A-14. Occurrence of Parameter Measurement and Frequencies in the Southwest (Sample Includes Streams in Texas and Oklahoma)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	51	1	4		33		13			
Turb.	4	1			3					
Color	3				1	1	1			
Odor										
pH	55	1			29	5	20			
Sus. Solids										
Dis. Solids	70	8			32	8	22			
Chloride	9				3	3	3			
Nutrients (N)	12	1				1	8			2
Nutrients (P)	28	13			11		2			2
Com. Ions	61	1			30	8	22			
Hardness	36	2			17	9	8			
Radio Chem.	2	2								
D.O.	6					1	3			2
Coliform	1					1				
Totals	338	30	4		159	37	102			6

†Frequency
Code:
* Not Periodic
1 Continuous
2 Seasonal
3 Daily
4 Weekly
5 Monthly
6 Quarterly
7 Annually
8 Other Periodic

Table A-15. Occurrence of Parameter Measurement and Frequencies in the Southwest (Sample Includes Streams in Texas, New Mexico, and Arizona)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	71		5		20	3	18	13	1	11
Turb.	10					2	1	3	1	3
Color	13					2	2	5	1	3
Odor	8						1	3	1	3
pH	52				9	2	16	12	1	12
Sus. Solids										
Dis. Solids	53	1	1		9	6	16	14	1	5
Chloride	36				9		14	2	1	10
Nutrients (N)	33	1			9	1	15	4	1	2
Nutrients (P)	17	3	1		1		4	3		5
Com. Ions	58	2	1		9	1	17	14	2	12
Hardness	43				9	3	16	9	1	5
Radio Chem.	11	5	1				3		1	1
D.O.	19					2	9	3	1	4
Coliform	11	1	1			1	8			
Totals	435	13	10		75	23	140	85	13	76

†Frequency Code:			
	* Not Periodic	3 Daily	6 Quarterly
	1 Continuous	4 Weekly	7 Annually
	2 Seasonal	5 Monthly	8 Other Periodic

Table A-16. Occurrence of Parameter Measurement and Frequencies in the West (Sample Includes Streams in California)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	74	2	10	8	4		23	6	13	8
Turb.	15	4					3	1		7
Color	6						6			
Odor	6						6			
pH	50	4		8			20	5	13	
Sus. Solids	6						3			3
Dis. Solids	53	4		4			17		13	15
Chloride	34						14	1	13	6
Nutrients (N)	28	4					20	1		3
Nutrients (P)	19	4			1		10	1		3
Com. Ions	53	4		8			18	5	16	2
Hardness	20	4					11	1		4
Radio Chem.										
D.O.	48			8			27	6		7
Coliform	20						17		3	
Totals	432	30	10	36	5		195	27	71	58

†Frequency Code:

* Not Periodic	3 Daily	6 Quarterly
1 Continuous	4 Weekly	7 Annually
2 Seasonal	5 Monthly	8 Other Periodic

Table A-17. Occurrence of Parameter Measurement and Frequencies in the Northwest (Sample Includes Streams in Oregon and Washington)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	76		23		17	10	21			5
Turb.	22	1			2	10	4			5
Color	7					2	4			1
Odor										
pH	13	1				1	7			4
Sus. Solids										
Dis. Solids	12	1				2	6			3
Chloride	4						4			
Nutrients (N)	8	1				1	4			2
Nutrients (P)	15	2			2	6	3			2
Com. Ions	11	2				4	5			
Hardness	13	1				2	6			4
Radio Chem.	2	1								1
D.O.	25				2	9	12			2
Coliform	3						2			8
Totals	211	10	23		23	47	78			37

†Frequency Code:

- * Not Periodic
- 1 Continuous
- 2 Seasonal
- 3 Daily
- 4 Weekly
- 5 Monthly
- 6 Quarterly
- 7 Annually
- 8 Other Periodic

Table A-18. Occurrence of Parameter Measurement and Frequencies in the Northwest (Sample Includes Streams in Washington)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	77	3	8		6	17	10	4	3	26
Turb.	24		1			15	8			
Color	24	3		1	3	1	9	7		
Odor	4						4			
pH	51	3		1	3	1	9	7	3	24
Sus. Solids										
Dis. Solids	24	3		1	3	2	4	7		4
Chloride	19	3		1	3		5	7		
Nutrients (N)	45	3		1	3	3	9	7		19
Nutrients (P)	36	12		1			6			17
Com. Ions	53	4		1	3	2	9	7	3	24
Hardness	21	3		1	3	2	5	7		
Radio Chem.	2	1				1				
D.O.	39	3				3	9	7		17
Coliform	34	4			1	15	8	6		
Totals	453	45	9	8	28	62	95	66	9	170

†Frequency Code:
* Not Periodic
1 Continuous
2 Seasonal
3 Daily
4 Weekly
5 Monthly
6 Quarterly
7 Annually
8 Other Periodic

Table A-19. Occurrence of Parameter Measurement and Frequencies (Totals Based on 1440 Stations from the Index to Water Quality)

Parameter	Tot.	Frequency†								
		*	1	2	3	4	5	6	7	8
Temp.	1191	23	118	13	160	78	366	153	102	178
Turb.	502	13	5	1	52	61	176	108	5	81
Color	666	19	0	1	22	40	195	133	116	140
Odor	234	10	0	0	9	6	83	82	1	43
pH	910	38	2	13	93	31	253	131	156	193
Sus. Solids	202	0	0	0	0	12	94	69	4	23
Dis. Solids	836	34	1	9	51	63	212	133	155	178
Chloride	661	8	1	1	22	25	242	85	117	160
Nutrients (N)	660	17	1	7	22	29	228	121	101	134
Nutrients (P)	664	43	2	7	25	17	156	142	103	169
Com. Ions	942	63	1	15	81	44	260	135	162	181
Hardness	763	59	1	6	63	56	243	107	139	89
Radio Chem.	208	40	1	1	2	1	33	79	40	11
D.O.	672	10	13	10	19	54	256	101	105	104
Coliform	542	10	1	0	44	62	217	125	6	77
Totals	9653	387	147	84	665	579	3011	1704	1312	1761

†Frequency Code:

*** Not Periodic**	**3 Daily**	**6 Quarterly**
1 Continuous	**4 Weekly**	**7 Annually**
2 Seasonal	**5 Monthly**	**8 Other Periodic**

APPENDIX B

ANALYSIS OF FEDERAL-STATE WATER QUALITY STANDARDS

This appendix reports a review of the federal-state stream water quality standards.

The objectives of the review were: 1) to determine the extent to which the stream standards were quantitative, and 2) the mathematical form of those standards which had been quantified. A secondary objective of the review was the identification of factors in the stream standards which would provide constraints on the way parameters were sampled. It was recognized that the standards might, in fact, already specify sampling schemes.

Copies of the currently approved federal-state water quality standards were requested from 20 states by telephone in July, 1971. Additionally, copies of current standards were solicited by mail from the remaining 30 states, the District of Columbia and several of the territories, in November, 1971. Responses were received from 44 of the 50 states, the District of Columbia, and Guam.

The results of the survey are presented in Table B-1. The states which responded are listed along the left- and right-hand margins of the table. Most states classify their waters according to the desired use of the water, and the appropriate water use classification is listed in the column next to the state name. Each subsequent column corresponds to a water quality parameter identified in the standards. Not all the parameters mentioned in the standards are listed in Table B-1; those listed are the most common. The standards are categorized into eight groups. The number designating the proper category is listed in the parameter column for each state. If no category is listed, the parameter is not mentioned in that state's standards.

The categorization of the standard is a matter of judgment on the part of the reviewer. Some errors may exist in Table B-1 due to lack of knowledge of the specific interpretations used in individual states. The judgments are based on the standards as supplied to us by the states in July and November, 1971. No attempt should be made to interpret the results summarized in Table B-1 as a measure of the "goodness" of a particular state's standards, due to varying interpretations, implementations, and legal structures in the states. The meaning of each category is given below, followed by a summary discussion.

Category 1 indicates a general narrative standard, not keyed to a particular quantitative value of the parameter.

Category 2 indicates a simple upper limit, a "not-to-exceed" (NTE) threshold; e.g., "temperatures not to exceed 78° F at any time."

Category 3 indicates a simple lower limit, a "not-less than" (NLT) threshold; e.g., "dissolved oxygen not less than 5 mg/1 at any time."

Categories 4 and 5 indicate the parameter is keyed to a statistical value; e.g., "temperatures not to exceed an average of 72° F," with 4 assigned to the NTE condition and 5 assigned to NLT.

Category 6 indicates the threshold is referenced to ambient natural conditions; e.g., "temperatures not to exceed 2° F above that expected due to natural causes."

Category 7 indicates a threshold with an associated duration; e.g., "dissolved oxygen not less than 75% saturation, 16 hours/day, and not less than 5 mg/1 at any time."

Category 8 indicates the kind of complex statistical threshold typified by the coliform standard; e.g., "coliform bacteria not to exceed a median of 1000 per 100 ml nor more than 2400 in more than 20% of the samples collected."

A number of conclusions may be drawn from the information in Table B-1.

The water quality standards in force at the time of the survey most generally apply to a limited number of water quality parameters. Those most frequently cited are:

- Dissolved oxygen
- Coliform count
- pH
- Temperature
- Radioactivity
- Toxicity
- Sludge deposits
- Color
- Turbidity
- Taste
- Odor
- Floating materials and debris

Of those, only the first four:

- Dissolved oxygen
- Coliform count
- pH
- Temperature

are consistently given in quantitative form, although the others are occasionally given numerical values.

LEGEND FOR TABLE B-1

DOM - Domestic
REC - Recreational
F&W - Fish and Wildlife
AG - Agriculture
PWS - Public Water Supply
IWS - Industrial Water Supply
AL - Aquatic Life
FW - Fresh Water
TYP - Typical
SF - Shellfish
NAV - Navigation
INTER - Intermittent Streams
MAX - Most Stringent Case

* - According to U.S. Public Health Service Drinking Water Standards
1 - Narrative
2 - "NTE" Threshold
3 - "NLT" Threshold
4 - Statistical "NTE" Threshold
5 - Statistical "NLT" Threshold
6 - Threshold Referenced to Ambient
7 - Threshold with Duration
8 - Complex Statistical Threshold

STATE	CLASSIFICATION	DISSOLVED OXYGEN	COLIFORM BACTERIA	pH	TEMPERATURE	CHEMICAL CONSTITUENTS	ARSENIC	BARIUM	BORON	CADMIUM	CHLORIDE	CHROMIUM	COPPER	CYANIDES	FLUORIDES	IRON	LEAD	MANGANESE	NITROGEN COMPOUNDS	PHENOLICS
ALASKA	A	3	4	2, 3	2	1														
	B	3	6	2, 3	2	1														
	C	3	6	2, 3	1	1														
	D	3	6	2, 3	4, 6	1														
	E	3	1	2, 3	2	1														
	F	3	6	2, 3	2, 3	1														
	G	3	6	2, 3	2	1														
ARIZONA	DOM		6	2, 3, 6	2, 6															
	REC		6	2, 3, 6	2, 6															
	F&W	3	6	2, 3, 6	2, 6															
	AG			2, 3, 6																
ARKANSAS	TYP	3	6	2, 3	2, 6															
COLORADO	A	3	6	2, 3	1		2	2		2		2		2			2			
	B	3	6	2, 3	2															
	C	3		2, 3	2															
	D																			
CONNECTICUT	A	3, 7	6	1	1	1														
	B	3, 7	6	2, 3	2, 6	1														
	C	3, 7	6	2, 3	2, 6	1														
	D	3	1	2, 3	2, 6	1														
DELAWARE	TYP	3	6	2, 3	6															
FLORIDA	I	3	6	2, 3	1										2					2
	II	3	4	2, 3	1															
	III	3	6	2, 3	1															
	IV	3		2, 3																
	V	5		2, 3																
IDAHO	TYP	3	6	2, 3	2, 6	1														
ILLINOIS	TYP	3, 7	6	2, 3	2, 6															
INDIANA	PWS		6	2, 3	2		2	2		2		2	2	2	2	2	2	2	2	2
	IW	3, 6		2, 3	2, 6		2	2		2		2		2	2		2			
	AL	3, 5																		
	REC		6																	
	AG																			
IOWA	PWS		2				2	2		2		2		2	2		2			2
	AL	3, 7		2, 3	2, 6		2	2		2		2	2	2			2		2	2
	REC		2																	
KANSAS	TYP	3	6	2, 3	2, 6															
KENTUCKY	PWS		6				2	2		2		2		2	2		2			
	IWS			2, 3	2															
	AL	3, 7		2, 3	2, 6															
	REC		6																	
	AG																			
LOUISIANA	TYP	3	6	2, 3	2, 6															
MAINE	A	3	2	1	1	1														
	B1	3, 6	2	2, 3	1	1														
	B2	3, 6	2	2, 3	1	1														
	C	3	2	2, 3	1	1														
	D	3	1	1	1	1														
MARYLAND	I	3	2	2, 3	2															
	II	3	6	2, 3	2															
	III	3	2	2, 3	2															
	IV	6	2	2, 3	2															
	V	3		2, 3	2															
	VI	3		2, 3	2															
MASSACHUSETTS	A	3, 7	4	6	6	1														
	B	3, 7	6	2, 3	2, 6	1													6	2
	C	3, 7	1	2, 3	2, 6	1													6	2
	D	3	1	2, 3	2	1														
MICHIGAN	A	1	6	6	6						4	2		2					1	2, 6
	B	1	6	2, 3	2														1	
	C	3	6	2, 3, 6	2, 6														1	
	D	3	6	6															1	
	E	1	6	2, 3, 6	6														1	
MISSISSIPPI	PWS	3	6	2, 3	2, 6		2	2		2	2	2		2	2, 3		2			2
	SF	3	6	2, 3	2, 6															
	REC	3	6	2, 3	2, 6															
	F&W	3	6	2, 3	2, 6															2
	AG&IWS	3		2, 3	2, 6															
	NAV	3		2, 3	2, 6															
MONTANA	A OP		4	6	6															
	A CL		4	2, 3																
	B		6	2, 3																
	C		6	2, 3																
	D1	3	6	2, 3	6															
	D2	3	6	2, 3	6															
	D3	3	6	2, 3	6															
	E		6	2, 3																
	F			2, 3	1															
NEBRASKA	A	3, 5	6	2, 3	6															
	B	3, 5	6	2, 3	6															
	C	3	6	2, 3	2, 6				2										2	
	INTER		6	2, 3																
NEVADA	TYP	3, 6	6	2, 3, 4, 5	4				2		2		2						2	

Table B-1. Analysis of Federal–State Water Quality Standards (Sheet 1 of 6)

PHOSPHATES	SELENIUM	SILVER	SULFATE	ZINC	RADIOACTIVITY	TOXICITY	HARDNESS	TOTAL DISSOLVED SOLIDS	BOD	SLUDGE	COLOR	TURBIDITY	TASTE	ODOR	PETROCHEMICALS OIL & GREASE	FOAMING MATERIALS	FLOATING DEBRIS	SEWAGE & INDUSTRIAL WASTE	CLASSIFICATION	STATE
					•	1		2			2	2			1		1		A	AK
					•	1		1			2	2			1		1		B	
					•	1		1			2	2			1		1		C	
					•	1		1			2	2			1		1		D	
					•	1		1			2	2			1		1		E	
					•	1		2			1	1			1		1		F	
					•	1		1			2	1			1		1		G	
					1	1				1		2			1		1	1	DOM	AZ
					1	1				1		2			1		1	1	REC	
					1	1				1		2			1		1	1	F&W	
					1	1				1					1		1	1	AG	
					1	2				1	1	1	1	1	1		1		TYP	AR
	2	2			1			2		1	1	1	1	1	1		1	1	A	CO
					1					1	1	1	1	1	1		1	1	B	
					1					1	1	1	1	1	1		1	1	C	
					1			4		1	1	1	1	1	1		1	1	D	
										1	1	1	1	1					A	CT
										1	1	1	1	1					B	
										1	1	1	1	1					C	
										1	1	1	1	1					D	
			2		2	1	2	2			1	2	1	1		2			TYP	DE
						1								4				1	I	FL
						1								4				1	II	
						1					1	2	1	1				1	III	
											1	2	1	1				1	IV	
														1				1	V	
						1							1	1	1		1		TYP	ID
2	2	2		2	2	1			1/	1	1	1		1	1				TYP	IL
	2	2			2	1		2.4		1	1	1		2	1		1	1	PWS	IN
						1		2.4		1	1	1		1	1		1		IW	
						1				1	1	1	1	1	1		1		AL	
						2				1	1	1		1	1		1		REC	
					1	1				1	1	1			1		1		AG	
					2, 4						1			1	1		1	1	PWS	IA
				5							1			1	1		1	1	AL	
											1			1	1		1	1	REC	
								1			1	1	1	1	1		1	1	TYP	KS
	2	2			2	1		2.4			1			2	1		1	1	PWS	KY
						1		2.4			1			1	1		1	1	IRS	
						2					1			1	1		1	1	AL	
						1					1			1	1		1	1	REC	
						1					1			1	1		1	1	AG	
						2									1	1			TYP	LA
					1					1	1	1	1	1	1		1	1	A	ME
					1					1	1	1	1	1	1		1	1	B1	
					1					1	1	1	1	1	1		1	1	B2	
					1					1	1	1	1	1	1		1	1	C	
					1					1	1	1	1	1	1		1	1	D	
																			I	MD
																			II	
																			III	
																			IV	
																			V	
																			VI	
					8					1	1	1	1	1	1		1		A	MA
4					1					1	1	1	1	1	1		1		B	
4					1					1	1	1	1	1	1		1		C	
					1					1	1	1	1	1	1		1		D	
1					2	1		2							1		1		A	MI
1					1	1		1							1		1		B	
1					1	1		1							1		1		C	
1					1	1		2							1		1		D	
1					2	1		1							1		1		E	
	2	2						2											PWS	MS
						1													SF	
						1		2			1		1	1					REC	
						2		2					1	1					F&W	
								2											AG&IWS	
								2											NAV	
					1	1				1		6			1		1		A OP	MT
					1	1				1		6			1		1		A CL	
					1	1				1		1			1		1		B	
					1	1				1		2			1		1		C	
					1	1				1		2			1		1		D1	
					1	1				1		2					1		D2	
					1	1				1		2			1		1		D3	
					1	1				1		1			1		1		E	
					1	1				1		2			1		1		F	
					2	1		2.6				6	1	1	1		1		A	NE
						1		2.6				6	1	1	1		1		B	
						1		2.6				6	1	1	1		1		C	
												2			1		1		INTER	
2, 4					1			2.6		1	1	1	1	1	1				TYP	NV

Table B-1. Analysis of Federal–State Water Quality Standards (Sheet 2 of 6)

STATE	CLASSIFICATION	DISSOLVED OXYGEN	COLIFORM BACTERIA	pH	TEMPERATURE	CHEMICAL CONSTITUENTS	ARSENIC	BARIUM	BORON	CADMIUM	CHLORIDE	CHROMIUM	COPPER	CYANIDES	FLUORIDES	IRON	LEAD	MANGANESE	NITROGEN COMPOUNDS	PHENOLICS
NEW HAMPSHIRE	A	3	2	1	6															
	B	3	2	2 3	1															
	C	3		2 3	1															
	D	3			2															
NEW JERSEY	FW 1																			
	FW 2	3		2 3	1	1														
	FW 3	3		2 3	1	1														
NEW MEXICO	TYP	3	4	2 3	2 6						4									
NEW YORK	AA	3	2	2 3	2 6					2			2	2					2	
	A	3	2	2 3	2 6					2			2	2					2	2
	B	3	2	2 3	2 6					2			2	2					2	
	C	3		2 3	2 6					2			2	2					2	
	D	3		2 3	2 6					2			2	2					2	
NORTH CAROLINA	A I		4																	2
	A II	3 5	8	6	2 6															2
	B	3 5	8	6	2 6															
	C	3 5	8	6	2 6															
	D	3	8	6	2 6															
NORTH DAKOTA	TYP	3 5 7	8	2 3	2 6			2	2	2		2	2	2			2		2	
OHIO	PWS	5 7	8				2	2		2		2		2	2		2			
	IWS	5 7		2 3	2															
	AL "A"	5 7		2 3	2 6															
	AL "B"			2 3	2															
	REC		8																	
	AG																			
OKLAHOMA	TYP	3	8	2 3	2 6															
OREGON	TYP	3	8	2 3	2 6	2	2	2	2	2	2	2	2	2	2	2	2	2		2
PENNSYLVANIA	MAX	3 5	8	2 3	2 6						2		2	2	2	2		2		2
RHODE ISLAND	A	3 7	8	1	1	1														
	B	3 7	8	2 3	2 6	1														
	C	3 6	1	2 3	2 6	1														
	D	3	1	2 3	2	1														
SOUTH CAROLINA	AA	3 6	4		1															2
	A	3	8	2 3	2 6															2
	B	3	8	2 3	2 6															
	C	3	8	2 3	2 6															
SOUTH DAKOTA	1		8	2 3															2	
	2	3	8	2 3	2						4			2		4				
	3	3	8	1																
	4			2 3															2	
	5		8	1																
	6			2 3																
	7			2 3																
TENNESSEE	DOM	1	8	2 3	2 6															
	IWS	1		2 3	2 6															
	AL	3		2 3	2 6															
	REC	1	8	2 3	2 6															
	AG	1		2 3	1															
	F&W	1		2 3	1															
	NAV	1			1															
TEXAS	TYP	3	1 4	2 3	2 6						4									
UTAH	A	1		2 3		•														
	B	1	8	2 3		•														
	C	3	8	2 3		•														
	CC	3	8	2 3	2 6	•														
	CW	3	8	2 3	2 6	•														
	CN	3	8	2 3		•														
	D		8	2 3		•														
	E																			
	S					•														
VERMONT	A	6	2	6	6															
	B	3	3	2 3	6															
	C	3	2	2 3	6															
	D	3	2	2 3	6															
VIRGINIA	III	3 5	8	2 3	2 6		2	2	2	2	2	2	2	2	2	2	2	2	2	2
	IV	3 5	8	2 3	2 6		2	2	2	2	2	2	2	2	2	2	2	2	2	2
	V	3 5	8	2 3	2		2	2	2	2	2	2	2	2	2	2	2	2	2	2
	VI	3 5	8	2 3	2		3	2	2	2	2	2	2	2	2	2	2	2	2	2
WASHINGTON	LAKE	6	8	6	6															
	AA	3	8	2 3	2															
	A	3	8	2 3	2															
	B	3	8	2 3	2															
	C	3	4	2 3	2															
WEST VIRGINIA	TYP	3	8	2 3	2		2	2		2	2	2		2	2		2		2	2
WISCONSIN	PWS		8	2 0																
	AL	3 6			2 6															
	REC		8																	
	IWS	3 5		2 3	2															
WYOMING	TYP	3	8	2 3	2 6															
DISTRICT OF COLUMBIA	TYP	3 5	8	2 3	2 6															
V I																				

Table B-1. Analysis of Federal–State Water Quality Standards (Sheet 3 of 6)

PHOSPHATES	SELENIUM	SILVER	SULFATE	ZINC	RADIOACTIVITY	TOXICITY	HARDNESS	TOTAL DISSOLVED SOLIDS	BOD	SLUDGE	COLOR	TURBIDITY	TASTE	ODOR	PETROCHEMICALS OIL & GREASE	FOAMING MATERIALS	FLOATING DEBRIS	SEWAGE & INDUSTRIAL WASTE	CLASSIFICATION	STATE
						1				1	2	2		1	1				A	NH
						1				1	1	2		1	1				B	
						1				1	1	2		1	1				C	
						1				1	1	1		1	1				D	
																			FW 1	NJ
						1				1	1	1	1	1	1		1		FW 2	
						1				1	1	1	1	1	1		1		FW 3	
			4		1	2		4		1	1	1			1		1		TYP	NM
				2		1				1	1			1					AA	NY
				2		1				1	1			2					A	
				2		1				1	1								B	
				2		1				1	1								C	
				2						1	1								D	
					2	2				1	2	2	1	1	2		1	2	A I	NC
					2	1	2			1	1	1		1	1		1	1	A II	
						1				1	1	1			1		1	1	B	
						1				1	1	1			1		1	1	C	
						1				1	1	1			1		1	1	D	
1	2				1													1	TYP	ND
	2	2			2	1		5,7		1	1			4	1		1		PWS	OH
						1		4,7		1	1			1	1		1		IWS	
						1				1	1			1	1		1		AL "A"	
						1				1	1			1	1		1		AL "B"	
						1				1	1			1	1		1		REC	
						1				1	1			1	1		1		AG	
					1	1				1	1	1	1	1	1		1		TYP	OK
				2	2	1		2		1	1	2	1	1					TYP	OR
2			2		2		3	2,4			2	2,4		2					MAX	PA
					1					1	1	1	1	1					A	RI
					1					1	1	1	1	1					B	
					1					1	1	1	1	1					C	
					1					1	1	1	1	1					D	
						1							1	1			1		AA	SC
						1					1		1	1			1		A	
						1					1		1	1			1		B	
						1					1		1	1			1		C	
					1	1		4		1					1		1	1	1	SD
					1	1				1		6			1		1	1	2	
					1	1				1					1		1	1	3	
					1	1	4	4		1					1		1	1	4	
					1	1		4		1					1		1	1	5	
					1	1		4		1					1		1	1	6	
					1	1				1					1		1	1	7	
						1		7		1	1	1	1	1			1	1	DOM	TN
						1	1	7		1	1	1	1	1			1	1	IWS	
						1				1	1	1	1	1			1	1	AL	
						1				1	1	1	1	1			1	1	PFC	
						1	1			1							1	1	AG	
						1	1			1							1	1	F&W	
						1	1			1							1	1	NAV	
			4		1	1		4	4	1	1	1			1	1			TYP	TX
					2														A	UT
					2														B	
					1					1	1	1	1	1			1		C	
					1					1	1	1	1	1			1		CC	
					1					1	1	1	1	1			1		CW	
					1					1	1	1	1	1			1		CR	
					1														D	
																			E	
					2														S	
					1					1	1	1	1	1	1		1		A	VT
					1					1	1	1	1	1	1		1		B	
					1					1	1	1	1	1	1		1		C	
					1					1	1	1	1	1	1		1		D	
	2	2	2		2		2	2			2				2				III	VA
	2	2	2		2		2	2			2				2				IV	
	2	2	2		2		2	2			2				2				V	
	2	2	2		2		2	2			2				2				VI	
					1	1						6							LAKE	WA
					1	1						6							AA	
					1	1						6							A	
					1	1						6							B	
						1						6							C	
	2	2	3		2	2								4					TYP	WV
						1		2,4		1	1		1	1	1		1		PWS	WI
						1				1	1		1	1	1		1		AL	
						1				1	1		1	1	1		1		REC	
						1				1	1		1	1	1		1		IWS	
					1	1				1	1	2	1	1			1		TYP	WY
										1	1	1	1	1	1		1	1	TYP	DC

Table B-1. Analysis of Federal–State Water Quality Standards (Sheet 4 of 6)

STATE	CLASSIFICATION	DISSOLVED OXYGEN	COLIFORM BACTERIA	pH	TEMPERATURE	CHEMICAL CONSTITUENTS	ARSENIC	BARIUM	BORON	CADMIUM	CHLORIDE	CHROMIUM	COPPER	CYANIDES	FLUORIDES	IRON	LEAD	MANGANESE	NITROGEN COMPOUNDS	PHENOLICS
GUAM	PWS	2	9	5	2 6															
	IWS																		2	
	AG																			
	F&W	2		6	6															
	REC		8	2 3	2														6	
	NAV			2 3																

Table B-1. Analysis of Federal–State Water Quality Standards (Sheet 5 of 6)

PHOSPHATES	SELENIUM	SILVER	SULFATE	ZINC	RADIOACTIVITY	TOXICITY	HARDNESS	TOTAL DISSOLVED SOLIDS	BOD	SLUDGE	COLOR	TURBIDITY	TASTE	ODOR	PETROCHEMICALS OIL & GREASE	FOAMING MATERIALS	FLOATING DEBRIS	SEWAGE & INDUSTRIAL WASTE	CLASSIFICATION	STATE
2					2						1	1	1	1	1	1	1	1	PWS	GUAM
					2						1	[illegible]	1	1	1	1	1	1	IRR	
					2						1	1	1	1	1	1	1	1	AG	
[illegible]					2						1	1	1	1	1	1	1	1	FSW	
					2						1	1	1	1	1	1	1	1	REC	
					2						1	1	1	1	1	1	1	1	NAV	

Table B-1. Analysis of Federal–State Water Quality Standards (Sheet 6 of 6)

Chemical parameters are infrequently cited (18 states of the 46 shown) and are given in quantitative form only when listed separately by ion or compound. Toxicity, cited by 26 of the 46 states listed, may be taken to include chemical constituents, but is quantified for one or more water uses in only 15 of those states.

Of those standards which are quantitative, 80% fall into the simple threshold categories (Categories 2 and 3), either alone or in combination with another category. Another 10% of the quantitative standards are in Category 8 (complex statistical threshold), accounting for a total of 90% in categories 2, 3, and 8.

Category 8 appears only in the coliform parameter column, comprising 80% of the quantified standards for that parameter. Another 15% of the quantitative coliform parameter standards are Category 2 type.

The significance of these observations to the development of the quantitative procedure lies in several areas.

First, it appears that the simple threshold case should be the focus for the development of the quantitative preliminary design procedure. It is the form most commonly found in the quantitative standards. The evidence of Table B-1 indicates that the simple threshold will dominate the standards for chemical constituents, as more states augment their standards in that area.

Second, it may be anticipated that a number of parameters listed as having predominantly narrative standards may become commonly quantitative (again in Category 2 form). The observation is based on the occasional mention of quantitative standards for these parameters:

- Toxicity
- Color
- Turbidity
- Taste
- Color

A number of observations affecting the formulation of quantitative preliminary design methods based on water quality standards are not summarized in Table B-1.

In general, the standards give no details of the sampling procedure to be used, even when the standards clearly imply sampling. Use of Category 4, 5, 7 and 8 standards sets a requirement for sampling, but the length of time over which averages were to be computed were rarely stated. The Category 8 coliform standards are obviously based on the USPHS Drinking Water Standards [22]. The drinking water standards have an established rule for sampling, but rarely was this rule explicitly cited.

All the states gave cognizance to the mixing-zone requirement, and this factor must be included in procedures for establishing station locations.

In addition, nearly all the states' standards contained a "nondegradation clause." The clause requires the preservation of stretches or bodies of water which presently have very high quality. This presents a requirement for long-term monitoring of these regions.

A number of the states gave standards which varied seasonally, monthly, or in some other fashion. Temperature was one parameter which was frequenly given in this way. Use of these standards in the quantitative preliminary design procedure will require some flexibility in the procedure.

In summary, it is believed that a quantitative procedure designed to meet the requirements of Category 2 and 3 standards will find the most general applicability now and in the future. No attempt need be made to deal with Category 8 standards, since procedures for drinking water sampling are already well established [22, 23, 24]. The standards do not, in general, form a constraint on the detailed sampling procedures employed.

APPENDIX C

DERIVATION OF SEGMENT PRIORITY RATING

In this appendix, the theoretical development of the segment priority rating is presented. The development is given in terms of the BOD-DO case, which is a nonconservative, coupled process. The class of parameters which may be described as nonconservative coupled is limited, but it constitutes the most difficult and most general mathematical form found in Simplified Mathematical Modeling of Water Quality [4]. The other two classes of parameters (nonconservative noncoupled and conservative) may be thought of mathematical subsets of the nonconservative, coupled class.

For this development, the basin is assumed to be segmented as described in Section VI and Appendix G. The discussion is in terms of a single segment and a single parameter in that segment.

The theoretical rating of need to monitor a particular segment for a particular parameter is based on the likelihood (or probability) of a violation of the water quality standard for the parameter within that segment. If a particular segment has a probability of violation higher than that of another segment, it will have a higher priority rating than the other segment. The probability of violation associated with the segment is the greatest probability found anywhere within the segment.

It is assumed that, at a given point x below the upstream end of the segment, the DO concentration (C) will be a random variable which is Gaussianly distributed. This assumption is made for two reasons: 1) for mathematical tractability, and 2) on a general appeal to the central-limit theorem [45]. The Gaussian assumption is analyzed in detail later in this appendix. This assumption allows the distribution of DO concentration (p(C)) to be described in terms of only the first two moments, the mean ($\bar{C}$) and the standard deviation (σ_C).

The probability of violation (π_v) under the Gaussian assumption is:

$$\pi_v = \Pr(C < C_T) = \int_{-\infty}^{C_T} p(C)\, dC$$

$$= \frac{1}{\sqrt{2\pi}\,\sigma_c} \int_{-\infty}^{C_T} \exp\left[-(C-\bar{C})^2/2\sigma_c^2\right] dC \tag{C-1}$$

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where

C_T = the threshold standard for dissolved oxygen concentration

See Figure C-1 for a graphical interpretation of the integral. If a change of variables is made, such that

$$s = \frac{C - \overline{C}}{\sigma_c} \tag{C-2}$$

Equation (C-1) becomes:

$$\begin{aligned} \pi_v &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\alpha} e^{-s^2/2}\, ds \\ &= \text{erf}\ (\alpha) \end{aligned} \tag{C-3}$$

where:

$$\alpha = \frac{C_T - \overline{C}}{\sigma_c} \tag{C-4}$$

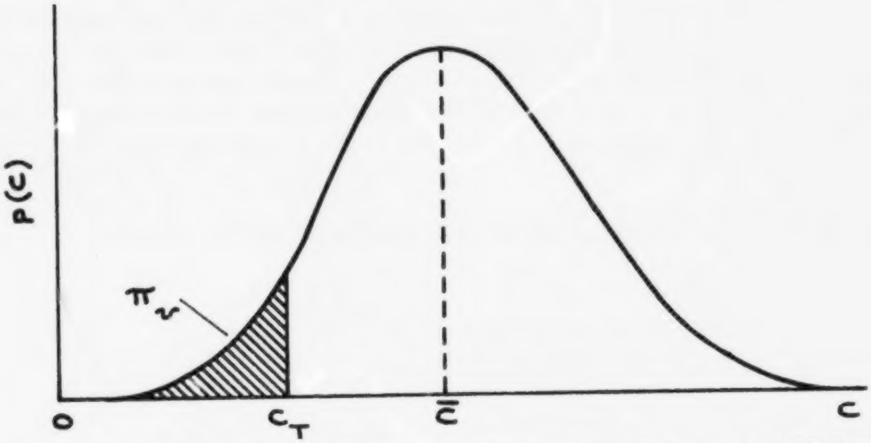

Figure C-1. Probability of Violation (π_v) Under Gaussian Assumption for NLT Standard

The probability of violation, π_v, is a monotonically increasing function of α, and ranges from zero to unity (Figure C-2).

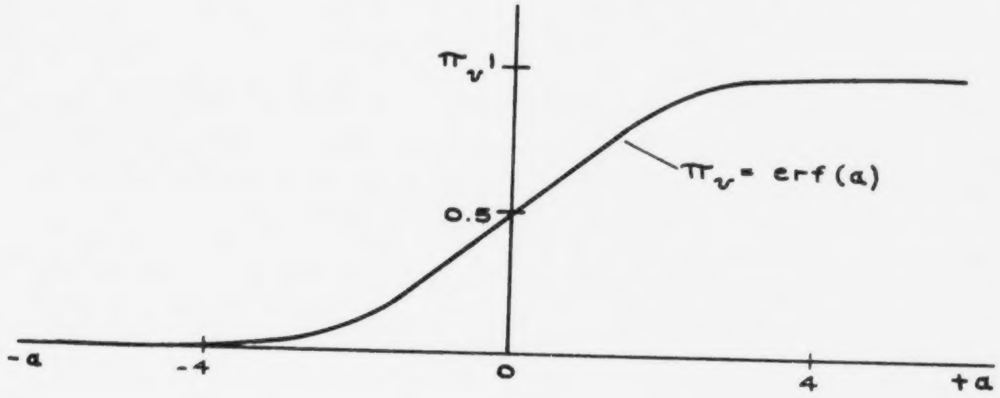

Figure C-2. Probability of Violation (π_v) as a Function of α

Thus, probability of violation is a suitable measure of the need to monitor a segment. It satisfies all the conceptual requirements for such a measure. It ranges from 0 to 1 and it is monotonically increasing. It is a function of the expected concentration of the water quality parameter, of the physical variability of the parameters, and of the threshold value established by the standards.

Because of the monotonic relationship between π_v and α, α is a "sufficient statistic" [46] for rating segment priority. It is obvious that its range does not satisfy the conceptual requirement of running from 0 to 1. However, it does preserve the order of ranking and it tends to provide additional resolution at the high- and low-priority ends of the scale.

Thus, α is a suitable representation of π_v as a measure of the need to monitor a segment. It has the advantage of direct computation without table-lookup or need of integration.

Notice, the definition of α used here is specific to processes which have a lower limit threshold, such as DO. The integration in Equation (C-1) would be done between C_T and positive infinity for cases in which the threshold constitutes an upper limit. For the "not-to-exceed" cases:

$$\alpha_{NTE} = \frac{\bar{C} - C_T}{\sigma_c} \qquad \text{(C-5)}$$

and, as before, for the "not-less-than" cases:

$$\alpha_{NLT} = \frac{C_T - \overline{C}}{\sigma_c} \tag{C-6}$$

Methods for estimation of α are explored and developed in Appendix D.

It has been assumed in the foregoing development that the water quality parameters under consideration behave according to the Gaussian probability density function. The assumption is made for mathematical tractability, because the Gaussian is a familiar form. It is also made by appeal to the central-limit theorem. Due to the physical properties of most water quality parameters, the assumption is not entirely accurate. It is the purpose of the following to assess the magnitude of the errors occurring from use of the Gaussian assumption.

One of the essential physical properties of most water quality parameters is that they are concentrations of constituents. Even pH and temperature may be thought of in those terms, one as the concentration of hydrogen ions and the other as the concentration of heat. Hence, each parameter possesses a fixed, absolute physical lower limit of concentration, in most cases equal to zero. (Temperature is unique in this regard, due to the definition of the fahrenheit and celsius temperature scales. Effectively, its lower limit may be taken as the freezing point, approximately 0° celsius.) In addition, there is typically a variable upper limit of concentration equal to the saturation concentration, which is at least a function of temperature. (Again, water temperature is unique; with a physical limit at the boiling point. Experience indicates a somewhat lower practical limit in streams.)

Therefore, a correct distribution for water quality parameters would have zero value for values of the parameter less than zero or greater than the saturation value (except where the finite probability of super-saturation is considered). The Gaussian clearly does not fit these requirements, since it has a finite value over the range $-\infty$ to ∞. As the mean value approaches zero, the error could become large, unless the variance becomes proportionately smaller.

A probability density function which more closely resembles that required by the physical properties is the Rayleigh distribution.

The Rayleigh distribution is defined as:

$$p(C) = \begin{cases} \frac{C}{\psi^2} \exp\left(-\frac{C}{2\psi^2}\right), & C \geq 0 \\ 0, & \text{otherwise,} \end{cases} \tag{C-7}$$

where ψ is the parameter of the Rayleigh distribution.

The mean and standard deviation of the Rayleigh distribution are, respectively:

$$\mu = \sqrt{\frac{\pi}{2}}\ \psi \tag{C-8}$$

$$\sigma = \sqrt{\frac{4 - \pi}{2}}\ \psi \tag{C-9}$$

The distribution is shown in Figure C-3, along with a Gaussian distribution, for comparison. Although the Rayleigh distribution may not entirely accurately portray the actual physical properties, it is used here for comparison because it is more representative than the Gaussian for cases of $\overline{C} << C_{sat}$.

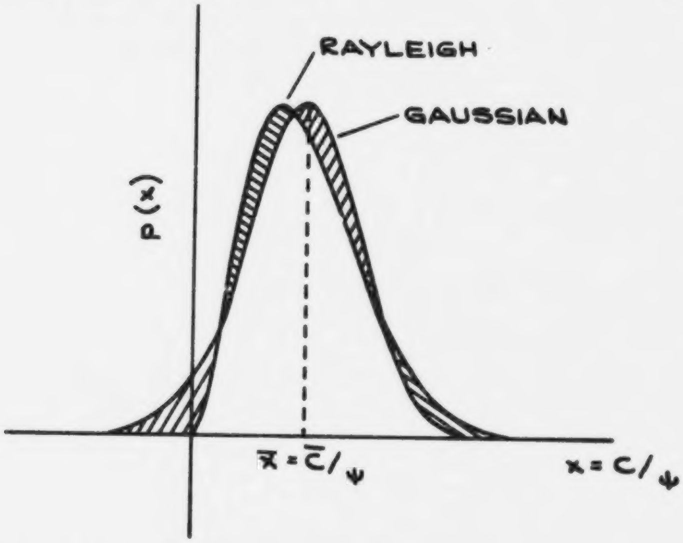

Figure C-3. Comparison of Gaussian and Rayleigh Distributions With Equal Mean and Standard Deviation

The comparison between the Rayleigh distribution and the Gaussian is typical of the kinds of errors which may be expected from use of the Gaussian in the quantitative procedure. The comparison is made in Figures C-4 and C-5.

In Figure C-4 it can be seen that the maximum error between the two distributions is approximately 0.1 σ (assuming the two distributions have the same mean and standard deviation). The maximum error in probability of violation is even smaller, less than 0.05, as shown in Figure C-5.

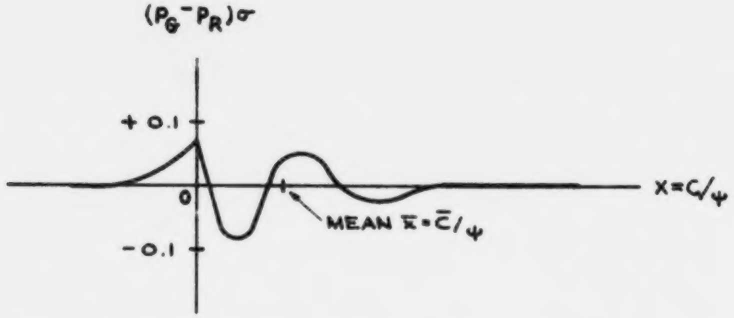

Figure C-4. Difference Between Gaussian (P_G) and Rayleigh (P_R) Distributions for Equal Mean and Standard Deviations

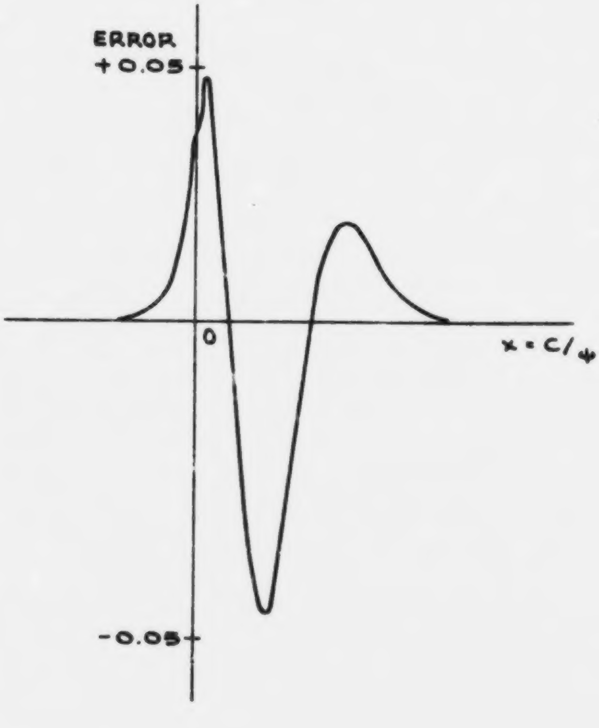

Figure C-5. Error in π_y Resulting from Use of Gaussian in Place of Rayleigh Distribution

Another factor affecting the validity of the Gaussian assumption is the periodicity of many of the water quality parameters. The periodicity may be due either to the direct influence of annual cyclic variation in rainfall and solar radiation to the direct influence of seasonal variability in industrial production or population, or to short-term changes, such as weekly industrial cycles.

In this case, the concentration of the parameter may be thought of as the superposition of two processes, one Gaussian random and the other periodic. Graphically, this superposition may be shown as a sequence of Gaussian distributions, with time-varying mean (Figure C-6). Since the concept of system duration (Section VI) requires that the segment priority be computed as the average segment priority over the system duration:

$$\text{Priority} = \text{AVE}\left[\pi_V\right] = \text{AVE}\left[\text{erf}(\alpha)\right] \qquad \text{(C-10)}$$

where AVE = the temporal average.

It can be shown [45] that:

$$E\left[f(x)\right] = \int_{-\infty}^{\infty} f(x)\, p(x)\, dx \qquad \text{(C-11)}$$

where

E = expected value (or ensemble average)

x = a random variable

p(x) = the probability density function of x

f(x) = any function of x

It can also be shown that, for stationary processes [47] :

$$\text{AVE}\left[f(x)\right] = E\left[f(x)\right] \qquad \text{(C-12)}$$

If f(x) is a linear function of x, then, from Equations (C-11) and (C-12)

$$\text{AVE}\left[f(x)\right] = f(\bar{x})$$

where

$$\bar{x} = \text{AVE}\left[x\right] .$$

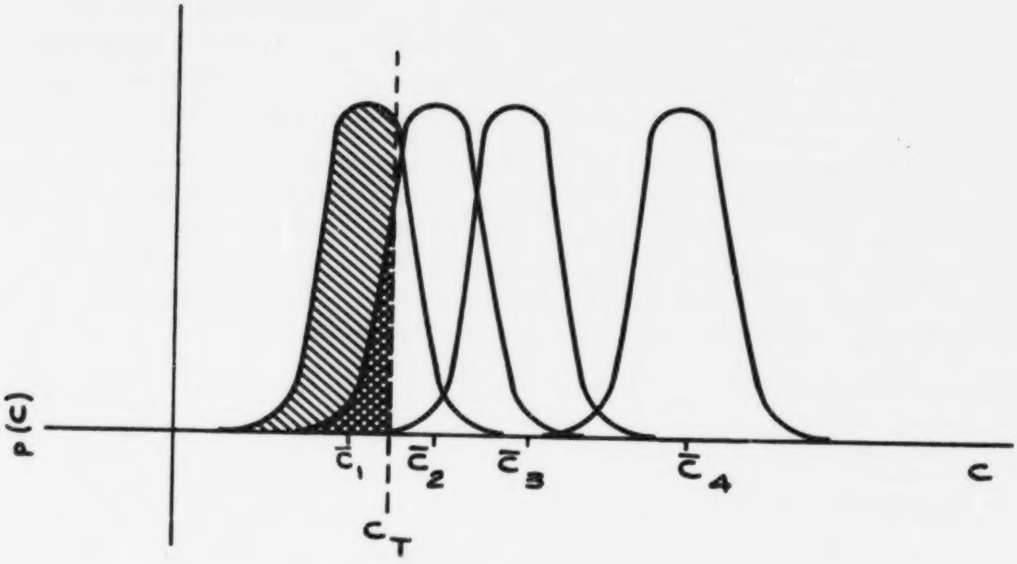

Figure C-6. Concept of Periodically Varying Gaussian Distribution

An examination of Figure C-2 indicates that π_V is approximately a linear function of α for large sections of the range of α. Thus, it may be concluded that, to a good approximation:

$$\text{Priority} = \text{AVE}\,[\pi_V] \simeq \text{erf}\,(\bar{\alpha}) \qquad \text{(C-13)}$$

Using the same arguments, it can be shown that:

$$\bar{\alpha} = \frac{C_T - \text{AVE}\,[\bar{C}]}{\sigma_c}$$

(Notice, it has been tacitly assumed that standard deviation does not vary significantly with time of year.)

Thus, α remains a suitable measure of the segment priority under conditions of periodic fluctuation.

It is concluded from these comparisons that the Gaussian distribution is a sufficiently good estimate of the probability density functions of the water quality parameters.

It is also concluded that α is a sufficiently good measure of segment priority. Therefore, the segmenty priority (P) is defined as:

$$P \equiv \alpha = \begin{cases} \dfrac{C_T - \overline{C}}{\sigma_c} & \text{for NLT thresholds} \\ \dfrac{\overline{C} - C_T}{\sigma_c} & \text{for NTE thresholds.} \end{cases} \qquad \text{(C-14)}$$

APPENDIX D

ESTIMATION OF THE SEGMENT PRIORITY

Determination of the segment priority requires the estimation of P (see Appendix C) from known quantities that describe the mean river water quality ($\bar{C}$) and the variability of that quality (σ_c). Appendix A and the discussion in Section VI indicate the generally limited usefulness of direct data on water quality. Since data on stream flow and effluents are somewhat better (albeit still poor), mathematical models of water quality may be used to evaluate the stream characteristics, and coefficients descriptive of the physical processes. Using BOD-DO as an example, relationships for evaluating $\bar{C}$ and σ_c are developed and discussed in this appendix. While the relationships for $\bar{C}$ prove useful, further approximations are shown to be necessary for evaluating σ_c.

The equations relating a BOD discharge at the upstream end of a segment to the BOD (L (x, t)) and the DO deficit (D (x, t)) throughout the segment are:

$$\frac{\partial L}{\partial t} = -u(t)\frac{\partial L}{\partial x} - k_d L \qquad \text{(D-1)}$$

$$L(0, t) = L_o(t) \qquad \text{(D-2)}$$

$$\frac{\partial D}{\partial t} = -u(t)\frac{\partial D}{\partial x} - k_a D + k_d L \qquad \text{(D-3)}$$

$$D(0, t) = D_o(t) \qquad \text{(D-4)}$$

where $u(t)$ = velocity of the stream in the segment

k_d = BOD concentration decay rate

k_a = Re-oxygenation rate

This set of equations (the so-called Streeter-Phelps equations [4]) can be expanded to include diffusion, photosynthetic oxygen production, and BOD runoff and scour in a straightforward way [9]. These terms have been ignored here, because they are of secondary importance and their omission provides useful simplification. If $\bar{u}$, $\overline{L_o}$, $\overline{D_o}$ are the mean values of u (t), $L_o(t)$, and $D_o(t)$, respectively, then the average DO deficit profile through the segment from Equation (15) (see also [17, 18, 48]) is:

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$$\bar{D}(x) = \frac{k_d \bar{L}_o}{k_a - k_d}\left[\exp(-k_d x/\bar{u}) - \exp(-k_a x/\bar{u})\right] + \bar{D}_o \exp(-k_a x/\bar{u}) \qquad \text{(D-5)}$$

The expected DO profile, found using Equation (D-5), is:

$$\bar{C}(x) = \bar{C}_{SAT} - \bar{D}(x) \qquad \text{(D-6)}$$

where $\bar{C}_{SAT}$ is the mean DO at saturation.

Of the three parameters needed to evaluate P, $\bar{C}$ is found from Equation (D-6) and C_T is established by the standards, leaving only the standard deviation σ_c to be found. An expression for σ_c is developed below.

Equations (D-1) and (D-3) can be thought of as representing a "black box" with three stochastic inputs, $L_o(t)$, $D_o(t)$, and u(t), and a single stochastic output D (x, t), as in Figure D-1. The stream velocity, u(t), has been shown differently from L_o and D_o, because it enters the equations in a different way.

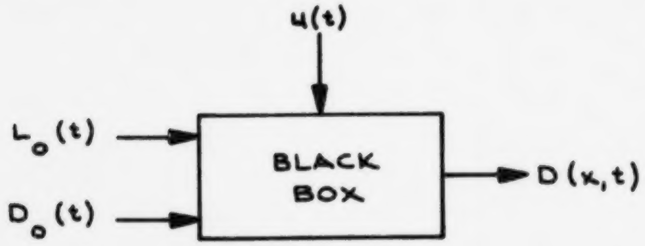

Figure D-1. Stochastic System for Analysis of Parameter Standard Deviation

Before considering the temporal variations in the output (as expressed by the standard deviation) due to the variations in all three inputs, the variations due to each input acting independently will be discussed.

Let $L_o(t)$ be a stochastic process with means $\bar{L}_o$ and standard deviation σ_{L_o}, and let D_o and u be constants with values $\bar{D}_o$ and $\bar{u}$, respectively. Then the expected value and standard deviation in the DO deficit are [48] :

$$\bar{D}(x) = \frac{k_d \bar{L}_o}{k_a - k_d}\left[\exp(-k_d x/\bar{u}) - \exp(-k_a x/\bar{u})\right] + \bar{D}_o \exp(-k_a x/\bar{u})$$

$$= A_1(\bar{u}, x)\,\bar{L}_o + A_2(\bar{u}, x)\,\bar{D}_o$$

and $\sigma_D = A_1(\bar{u}, x)\ \sigma_{L_o}$

Let $D_o(t)$ be a stochastic process with mean $\bar{D}_o$ and standard deviation σ_{D_o}, and let L_o and u be constants with values $\bar{L}_o$ and $\bar{u}$, respectively. Then, by a procedure similar to that in [47] :

$$\bar{D}(x) = A_1(\bar{u}, x)\,\bar{L}_o + A_2(\bar{u}, x)\,\bar{D}_o$$

and $\sigma_D(x) = A_2(\bar{u}, x)\ \sigma_{D_o}$ (D-8)

Let u(t) be a stochastic process with mean $\bar{u}$ and standard deviation σ_u, and let L_o and D_o be constants with values L_o and 0, respectively. Then [18] :

$$\bar{D}(x) = A_1(\bar{u}, x)\,\bar{L}_o$$

$$\sigma_D(x) = A_1(\bar{u}, x)\,\bar{L}_o\ \sigma_u \qquad \text{(D-9)}$$

By a similar procedure, if $L_o = 0$ and $D_o = \bar{D}_o$ (a constant), then:

$$\bar{D}(x) = A_1(\bar{u}, x)\,\bar{L}_o + A_2(\bar{u}, x)\,\bar{D}_o$$

$$\sigma_D(x) = A_2(u, x)\,\bar{D}_o\ \sigma_u \qquad \text{(D-10)}$$

Since Equations (D-1), (D-3), and (D-5) are linear in L_o and D_o, superposition may be applied to obtain the following result for the case in which $L_o = \bar{L}_o$, a constant, and $D_o = \bar{D}_o$, a constant:

$$\bar{D}(x) = A_1(\bar{u}, x)\,\bar{L}_o + A_2(\bar{u}, x)\,\bar{D}_o$$

$$\sigma_D(x) = \left\{\left[A_1(\bar{u}, x)\,\bar{L}_o\right]^2 + \left[A_2(\bar{u}, x)\,\bar{D}_o\right]^2\right\}^{1/2} \sigma_u \qquad \text{(D-11)}$$

However, u(t) enters Equations (D-1), (D-3), and (D-5) in a nonlinear way, so that superposition does not apply exactly. A first-order approximation can be made in which the "cross-variation" terms are neglected and the rms value for σ_D is found.

The standard deviation of the dissolved oxygen is then found by noting that Equation (D-6) relates $\bar{C}$ and $\bar{D}$ through a constant. Under that condition the variation in C (x, t) has the same magnitude as variations in D (x, t) and:

$$\sigma_C = \left[A_1^2 \sigma_{L_o}^2 + A_2^2 \sigma_{D_o}^2 + (A_1^2 L_o^2 + A_2^2 D_o^2)\, \sigma_u^2 \right]^{1/2} \tag{D-12}$$

with the right-hand side evaluated at the point in the stream where π_v is maximum (see Section VI).

Clearly, P can be partially evaluated by use of Equations (D-5) and (D-6) for computation of $\bar{C}$, but complete evaluation depends on the ability to derive σ_c from Equation (D-12). In general, information is lacking on two of the factors necessary to evaluate Equation (D-12), σ_{L_o} and σ_{D_o}. Estimation of the standard deviations of the parameter value at the upstream end of the segment requires knowledge of the variability of the sources. While relatively good methods are available to estimate mean source loading (see, for example, [4]), information on the standard deviation is generally not derivable from the available records and no comparable estimation methods have been developed.

For the purposes of preliminary design, it is assumed that the standard deviation is not a strong function of distance along the stream. It should be clear from Equation (D-12) that this assumption may be reasonably good for large x ("large" is left undefined).

Under this assumption, it is permissible to estimate σ_c from available historical water quality records at points some distance from the sources at the upstream end. While this method may be considered satisfactory for BOD-DO, which has a downstream minimum point, it is clearly less so for those parameters which have peak $\bar{C}$'s near the upstream end of a segment.

Thus, for purposes of preliminary design of water quality surveillance systems, the segment priority (P) is evaluated through use of mathematical models to estimate C and through use of historical water quality data to estimate σ_c. The evaluation is carried out at the point in the segment where probability of violation is a maximum (x_m) and σ_c is assumed constant throughout the segment.

APPENDIX E

DERIVATION OF PRIORITY MEASURE FOR SAMPLING FREQUENCY

This appendix presents the detailed derivation of the priority measure for sampling frequency (M) discussed in Section VI, (Equations (26) and (27)). It is based on the definition of the measure given in that section:

$$M = \frac{\text{Expected Number of Violations Detected}}{\text{Expected Number of Violations}} \qquad \text{(E-1)}$$

Let v(t) represent the time-varying magnitude of a water quality parameter, as shown in Figure E-1. If the quantitative threshold level defined by the water quality standards is V_o, a violation occurs when the parameter magnitude exceeds the threshold $[v(t) > V_o]$. (In some cases, such as dissolved oxygen, the violation occurs when $v(t) < V_o$ but this does not change the mathematical analysis, as will be seen). A normalized two-state process can be defined which equals unity during a violation and which equals zero when there is not a violation. Such a process is shown graphically in Figure E-1 as y(t).

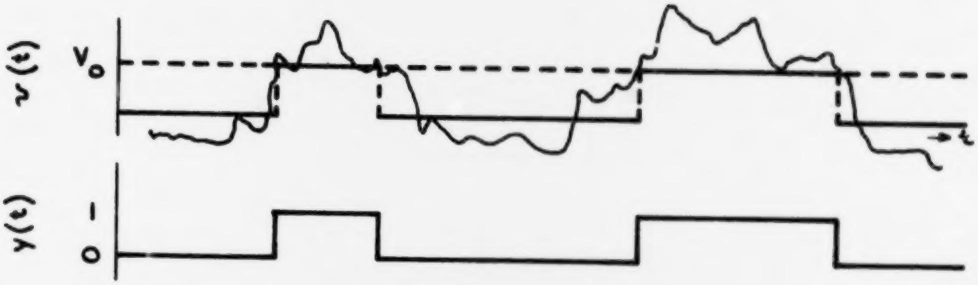

Figure E-1. Conversion of Parameter Process into Violation Process

To describe the stochastic process y(t), probabilities of transition from one state to the other are needed. In general, these probabilities are functions of the threshold level V_o (the normalizing factor) and the past history of y(t). As a first-order simplifying assumption, it is taken that the transition probabilities are explicitly dependent only on the present state (0 or 1) and on the length of time that x(t) has been in that state and implicitly on the threshold level V_o [49]. For the simplified case, sufficient descriptors of the stochastic process y(t) are:

$$\pi_i(t) \equiv \Pr[y(t) = i \mid y(0) = i] \qquad i = 0, 1 \qquad \text{(E-2)}$$

which are probabilities that, for time $t > 0$, y is in state i, given that it entered state i at time $t = 0$. Another way of stating it is that no transition occurs in time t, given that a transition occurred at time 0.

To further simplify the mathematics, it is assumed that y(t) is a Poisson process, a well-known process which satisfactorily describes many natural processes. This assumption reduces the probabilities in Equation (E-2) to the form:

$$\pi_i(t) = \exp(-t/T_i) \qquad i = 0,\ 1 \tag{E-3}$$

where T_i, $i = 0, 1$, is the mean time in state i before a transition occurs, and depends on the threshold level V_o.

These assumptions produce a simple mathematical description of the violation process in terms of two natural descriptors, the mean duration of a violation (T_1) and the mean interval between violations (T_o). Also, the probability of a violation (π_v) can be easily expressed in terms of the descriptors:

$$\pi_v = \frac{T_1}{T_1 + T_o} \tag{E-4}$$

Notice that computation of these probabilities for a real case requires the estimation of the descriptors T_o and T_1.

To derive Equation 29, define the sampling process S(t) in Figure E-2 as the periodic function:

$$S(t) = \begin{cases} 1/\epsilon & n\Delta < t < n\Delta + \epsilon\ ,\ n = 1,\ 2,\ \ldots \\ 0 & \text{elsewhere} \end{cases} \tag{E-5}$$

The sampled process $y_s(t)$ is:

$$y_s(t) \equiv y(t)\ S(t) \tag{E-6}$$

and

$$z(t) \equiv y(t) - y(t-\Delta) \tag{E-7}$$

$$z^+(t) \equiv \begin{cases} x(t) & \text{for } z(t) > 0 \\ 0 & \text{for } z(t) \leq 0 \end{cases} \tag{E-8}$$

$$z_s^+(t) \equiv z^+(t)\ S(t) \tag{E-9}$$

Since the pulses in z(t) are of length Δ or less, at most one sample will be taken during their existence. Hence, z_s^+ contains only the first sample in any string of samples associated with a single violation. The average number of detection pulse strings (denoted by n_d) is:

$$n_d = \lim_{T \to \infty} \frac{1}{T} \int_0^T z_s^+(t)\, dt \tag{E-10}$$

Assuming ergodicity, the time average is equal to the ensemble average, denoted as:

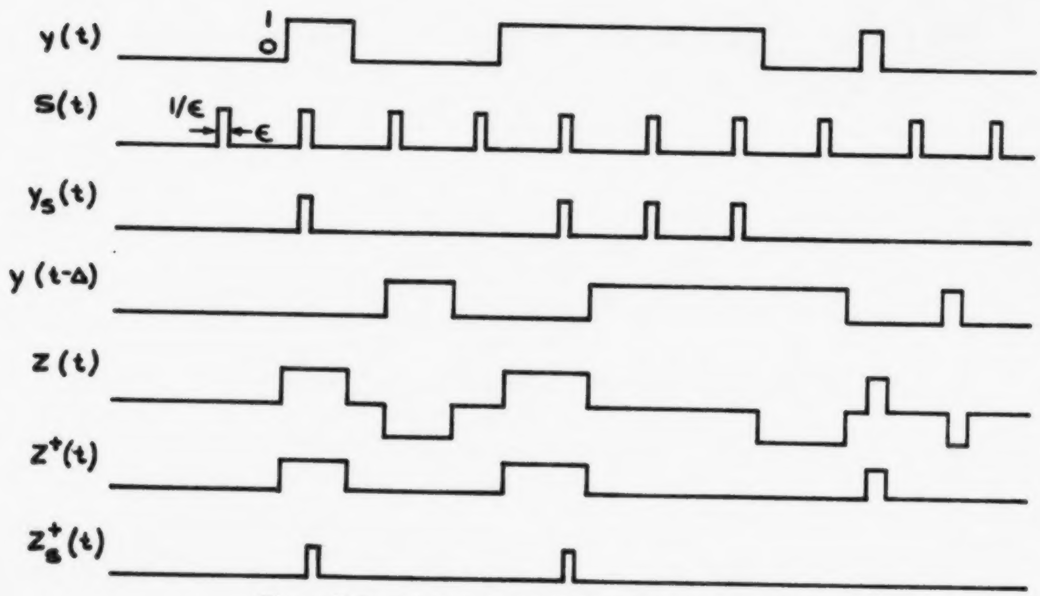

Figure E-2. Time-Series Violation Process Analysis

$$n_d = E\left[z_s^+\right] \tag{E-11}$$

which is:

$$\begin{aligned} n_d &= E\left\{\left[y(t) - y(t-\Delta)\right]^+ \ S(t)\right\} \\ &= E\left\{\left[y(t) - y(t-\Delta)\right]^+\right\} E\left[S(t)\right] \end{aligned} \tag{E-12}$$

since the processes y(t) and S(t) are independent.

Now:

$$E\left[S(t)\right] = \lim_{T\to\infty} \frac{1}{T} \int_0^T S(t)\ dt \tag{E-13}$$

$$= 1/\Delta$$

and

$$E\left\{\left[y(t) - y(t-\Delta)\right]^+\right\} = \Pr\left[y(t)=1,\ y(t-\Delta)=0\right] \tag{E-14}$$

$$= \Pr\left[y(t-\Delta)=0\right]\ \Pr\left[y(t)=1 \middle| y(t-\Delta)=0\right]$$

But:

$$\Pr\left[y(t-\Delta)=0\right] = \frac{T_o}{T_1 + T_o} \tag{E-15}$$

and

$$\Pr\left[y(t)=1 \middle| y(t-\Delta)=0\right] = \Pr\left[\text{odd-number transitions in } (0,\Delta) \middle| (y(0)=0\right]$$

$$= \sum_{n=1}^{\infty} \Pr\left[(2n-1) \text{ transitions in } (0,\Delta) \middle| y(0)=0\right] \tag{E-16}$$

The probability of one transition in $(0,\Delta)$ can be found by:

$$\Pr\left[1 \text{ transition in } (0,\Delta) \middle| y(0)=0\right] = \int_0^{\Delta} \Pr\left[\text{no transition in } (0,s) \middle| y(0)=0\right]$$

$$\cdot\Pr\left[\text{transition in } (s, s+ds)\right]$$

$$\cdot\Pr\left[\text{no transition in } (s+ds,\Delta) \middle| y(s+ds)=1\right]$$

$$= \int_0^{\Delta} \exp\left(\frac{-s}{T_o}\right)\frac{ds}{T_o}\ \exp\left[-\frac{(\Delta - s)}{T_1}\right]$$

$$= \frac{T_1}{T_o - T_1}\left[\exp\left(-\frac{\Delta}{T_o}\right) - \exp\left(-\frac{\Delta}{T_1}\right)\right] \tag{E-17}$$

In a similar manner, it can be shown that:

$$\Pr\left[(2n\text{-}1) \text{ transitions in } (0,\Delta) \,\middle|\, y(0)=0\right] = \frac{T_o^{n-1}\;T_1^{n}}{(T_o - T_1)^{2n-1}} \left[f_{0n} \exp\left(-\frac{\Delta}{T_o}\right) + f_{1n} \exp\left(-\frac{\Delta}{T_1}\right)\right] \qquad \text{(E-18)}$$

where

$$f_{0n} = \sum_{k=1}^{n} a_k^n \;\Delta^{k=1} \left[\frac{T_o - T_1}{T_o T_1}\right]^{k-1}$$

$$f_{1n} = \sum_{k=1}^{k} b_k^n \;\Delta^{k-1} \left[\frac{T_0 = T_1}{T_0 T_1}\right]^{k-1}$$

$$a_k^n = \frac{(-1)^{n-k}\;(2n-k-1)!}{(n-k)!\;(n-1)!\;(k-1)!}$$

$$b_k^n = (-1)^k \; a_k^n$$

By substituting Equations (E-17) and (E-18) into Equation (E-16):

$$\Pr\left[y(T) = 1 \,\middle|\, y(T-\Delta) = 0\right] = C_0 \exp\left(-\frac{\Delta}{T_0}\right) + C_1 \exp\left(-\frac{\Delta}{T_1}\right) \qquad \text{(E-19)}$$

where

$$C_0 = \sum_{n=1}^{\infty} \frac{T_0^{n-1}\;T_1^{n}}{(T_0 - T_1)^{2n-1}} \; f_{0n}$$

$$C_1 = \sum_{n=1}^{\infty} \frac{T_0^{n-1}\;T_1^{n}}{(T_0 - T_1)^{2n-1}} \; f_{1n}$$

Then, using Equations (E-19), (E-15), (E-14), and (E-13), the expression for n_d (Equation (E-12)) can be evaluated:

$$n_d = \left\{ \frac{T_0}{T_1 + T_0} \left[C_0 \exp(-\frac{\Delta}{T_0}) + C_1 \exp(-\frac{\Delta}{T_1}) \right] \right\} \left\{ \frac{1}{\Delta} \right\} \qquad \text{(E-20)}$$

The average number of violations (n_v) is:

$$n_v = \frac{1}{T_0 + T_1} \qquad \text{(E-21)}$$

Using Equation (E-20) and (E-21) in the definition of the priority measure yields:

$$M(\Delta, T_0, T_1) = \frac{n_d}{n_v} = \frac{T_0}{\Delta} \left[C_0 \exp(-\frac{\Delta}{T_0}) + C_1 \exp(-\frac{\Delta}{T_1}) \right] \qquad \text{(E-22)}$$

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In the above definition, it is tacitly assumed that $\Delta < T_0$. Under this assumption, a violation commencing shortly after termination of a preceding violation is considered part of the preceding violation. This is not a limitation for cases of interest.

Derivation of the approximate for M (M^*), given as Equation (27), is parallel to the derivation of M (above) until Equation (E-16). For the case $\Delta < T_0 + T_1$, the summation in Equation (E-16) becomes:

$$\sum_{n-1}^{r} \Pr\left[(2n-1) \text{ transitions in } (0, \Delta) \middle| y(0) = 0\right] = \Pr\left[1 \text{ transition in } (0, \Delta) \middle| y(0) = 0\right] \qquad \text{(E-23)}$$

Under this condition, Equation (E-17) replaces Equation (E-18) in the derivation of Equation (E-19). The result is:

$$M^*(\Delta, T_0, T_1) = \frac{T_0}{\Delta} \left[\frac{\exp(-\Delta/T_0) - \exp(-\Delta/T_1)}{T_0/T_1 - 1} \right] \qquad \text{(E-24)}$$

APPENDIX F

DERIVATION OF ESTIMATORS FOR T_o AND T_1

In this appendix, the assumptions and rationale employed in developing the procedure for rating sampling frequency are described. Since the procedure depends strongly on estimation of the descriptors T_o and T_1, derivation of the estimators is emphasized. The need for a description of the dynamics of water quality variations is identified first, then the quasi-steady-state description of those dynamics is presented. Next the application of the quasi-steady-state description is given, followed by the procedure for estimation of the average violation duration (T_1) and average interval between violations (T_o).

In Appendix E, the quantitative priority measure for rating sampling frequency is developed in terms of the dynamics of water quality violations at a point in the stream. The descriptors T_o and T_1 are used to describe the dynamics at the point. To obtain estimates of T_o and T_1, either the dynamics of water quality in the stream must be known or they must be describable in terms of known processes which cause them, such as stream flow and waste discharges. Since data on streamflow and discharges are either currently available or soon to be available (through the Refuse Act Permit Program or its replacement), the latter approach was selected, requiring the use of time-varying stream quality equations.

Equations which describe the time-varying water quality parameters along a stream are well known for all three classes of water quality parameters. They are described here in the most complex form, that of the nonconservative, coupled class represented by BOD-DO. Neglecting diffusion, the equations are:

$$\frac{\partial L}{\partial t} = -u \frac{\partial L}{\partial x} - k_d L \qquad \text{(F-1)}$$

$$\frac{\partial D}{\partial t} = -u \frac{\partial D}{\partial x} - k_a D + k_d L \qquad \text{(F-2)}$$

where L = BOD concentration

D = DO deficit concentration

u = stream velocity

k_a, k_d = reaeration and deoxygenation rate coefficients, respectively.

If $$L_o = L_o(t) \qquad \text{(F-3)}$$

$$D_o = D_o(t) \qquad \text{(F-4)}$$

are sufficiently slowly-varying BOD and DO deficit concentrations at the upstream end of a segment ($x = 0$), then the solutions to Equations (F-1) and (F-2), with initial conditions represented by Equations (F-3) and (F-4), are:

$$L(x, t) = L_o(t) \exp(-k_d x/u) \tag{F-5}$$

$$D(x, t) = \frac{k_d}{k_a - k_d} L_o(t) \left[\exp(-k_d x/u) - \exp(-k_a x/u) \right] + D_o(t) \exp(-k_a x/u) \tag{F-6}$$

These quasi-steady-state expressions are identical in form to steady-state expressions discussed in Section VI, except for the time-varying L_o and D_o. Using Equations (F-5) and (F-6), the dynamics of the deficit, $D(x_m, t)$, at the point x_m in the segment can be related to the dynamics of $L_o(t)$ and $D_o(t)$ at the upstream end of the segment. The $L_o(t)$ and $D_o(t)$ can then be expressed in terms of the BOD and DO deficit concentrations due to the upstream segment (L_e and D_e), the stream flow from the upstream segment (Q_e), the BOD discharge rate at the source (W_s), the flow from the source (Q_s), and DO deficit of the source (D_s). See Figure F-1. The relationships may be written as:

$$L_o(t) = \frac{Q_e L_e + W_s}{Q_e + Q_s} \tag{F-7}$$

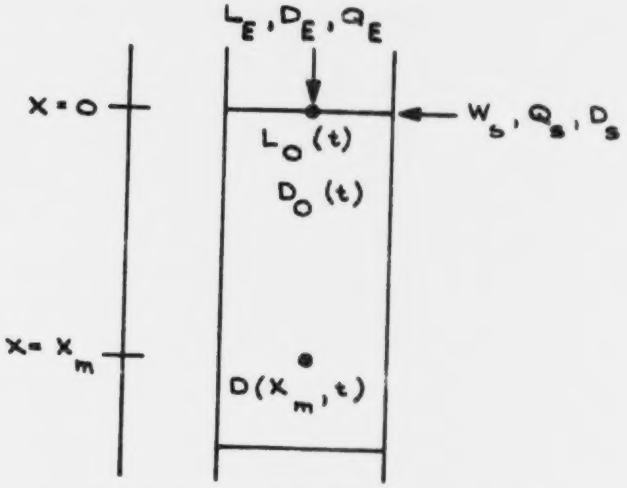


Figure F-1. Segment BOD-DO Situation Diagram

$$D_o(t) = \frac{Q_e D_e + Q_s D_s}{Q_e + Q_s} \qquad \text{(F-8)}$$

In many cases, the temporal variations in Q_e are larger than the variations in the other parameters on the right-hand side of Equations (F-7) and (F-8). Also, the variations in W_s, D_s, and Q_s are generally not well known. Hence, it will be assumed here that the dynamics of $L_o(t)$ and $D_o(t)$ are due entirely to the dynamics of $Q_e(t)$. Average values of W_s, D_s, Q_s, L_e, and D_e are used in evaluating these two equations.

For computational purposes, it is assumed that $W_e = Q_e L_e$ (the initial waste load due to the upstream segment) and $Q_e D_e$ are constant; the values used in establishing segment priority and spatial locations are assigned. In this case:

$$L_o(t) = \frac{\text{Constant}}{Q_e(t) + Q_s} \qquad \text{(F-9)}$$

$$D_o(t) = \frac{\text{Constant}}{Q_e(t) + Q_s} \qquad \text{(F-10)}$$

It can be seen that $L_o(t)$ and $D_o(t)$ vary in identical ways, as $Q_e(t)$ varies. Therefore, $D(x, t)$ varies with $Q_e(t)$ in the same way.

Furthermore, it follows that

$$\frac{D(x, t_1)}{Q_e(t_1) + Q_s} = \frac{D(x, t_2)}{Q_e(t_2) + Q_s} \qquad \text{(F-11)}$$

From Equation (F-11), it can be shown that there is a threshold value of stream-flow (Q_t) that is associated with the threshold value of DO deficit derived from the water quality standards. The relationship can be written as:

$$Q_T = \left[\frac{D(x_m, t)}{D_T}\right]\left[Q_e(t) + Q_s\right] - Q_s \qquad \text{(F-12)}$$

where D_T = the DO deficit threshold derived from the standards value for minimum DO

The descriptors T_o and T_1 may be estimated directly from statistics of Q_e, specifically the time Q_e spends above and below Q_T, respectively. Since a violation occurs if $D > D_T$, a violation occurs if $Q_e < Q_T$, from Equation (F-11). The time D spends at values greater than D_T is equal to the time Q_e spends at values less than Q_T. Thus, T_1 can be estimated by statistical examination of daily streamflow records, such as those available from the U.S. Geological Survey. Similarly, T_o may be estimated by statistics on the time $Q_e > Q_T$.

Since there may be more stream segments than stream gauging stations along a river, the nearest upstream or downstream station must be used. Selection should be made on the basis of which station can be expected to represent the segment best, for example, in the vicinity of a confluence point. It is possible to interpolate values between two stations, but it becomes impractical for the manual methods to be used in the procedures under consideration.

Once the estimates of T_o and T_1 have been found for each segment, the priority measure for sampling frequency may be evaluated using the methods derived in Appendix E.

APPENDIX G

USER HANDBOOK

This appendix constitutes a stand-alone handbook for the application of quantitative methods to the preliminary design of water quality surveillance systems.

Usage

The User Handbook is intended for use in determining the following water quality surveillance system design factors:

1) A numerical priority (P) for the measurement of each water quality parameter of interest in each stretch of the stream
2) A preferred location (x_m) for the measurement of each water quality parameter of interest in each stretch of the stream
3) A numerical rating of merit (M) for each candidate sampling frequency at the preferred location for measurement of each water quality parameter in each stretch of the stream.

The user may wish to determine these design factors for any of several reasons, such as:

1) The preliminary design of a new water quality surveillance system
2) Comparing an existing surveillance system against the recommendations of the procedure
3) Program planning to evaluate the overall level of surveillance required in a basin, region or nation.

Limitations

The User Handbook is limited to preliminary design of water quality surveillance systems which have abatement as the primary goal. It is intended that the resulting system detect violations of water quality standards. The methods require that the standards be expressed as a simple threshold, either directly or, indirectly, by arbitrary choice of the user.

The methods are limited to those cases in which the "macroscopic" concept holds. That is, the stream is considered as one-dimensional and periods of less than a day are ignored.

The user should be familiar with basic engineering mathematics up to, but not including, calculus. He should also have available a desk calculator or similar computational device. It is not necessary to have access to an automatic digital computer.

The User Handbook does not include consideration of cost, accessibility, maintainability, reliability and other similar practical engineering factors.

Overview of the Quantitative Procedures

The quantitative preliminary design procedure consists of a number of individual activities which have been grouped into six tasks. The six tasks are performed sequentially, beginning with Task 1 and proceeding to Task 6 (Figure G-1). The activities within each task may occur in either iterative or sequential patterns; flow charts have been provided with each task to guide the user.

In Task 1, the user will be concerned with gathering necessary data, organizing information and determining certain guidelines for his particular application.

Task 2 is devoted to the development of specific items of information which characterize the river basin. This is accomplished by manipulation of the data collected in Task 1.

In Task 3, the user begins the actual preliminary design by establishing stream segments, which are stretches of the stream which may be dealt with as uniform units.

The primary output of Task 4 is the location of preferred monitoring stations, although a number of other factors are computed for use in Tasks 5 and 6.

The priority of each parameter of interest to the user in each segment is established in Task 5.

Task 6 is concerned with the computation of a rating of the merit of various sampling frequencies proposed by the user.

Stream Quality Parameters

The design procedures are based on stream quality profiles of (water quality) design parameters of interest. Design parameters from three basic classes of parameters, including non-conservative coupled, non-conservative uncoupled and conservative, can be used in the procedures. Most stream quality parameters of interest are included in one of these classes, given in Table G-1. In the handbook procedures, the most general class (coupled) is presented in terms of the important doublet, BOD-DO.

Illustration

For computational efficiency an attempt has been made to use a consistent

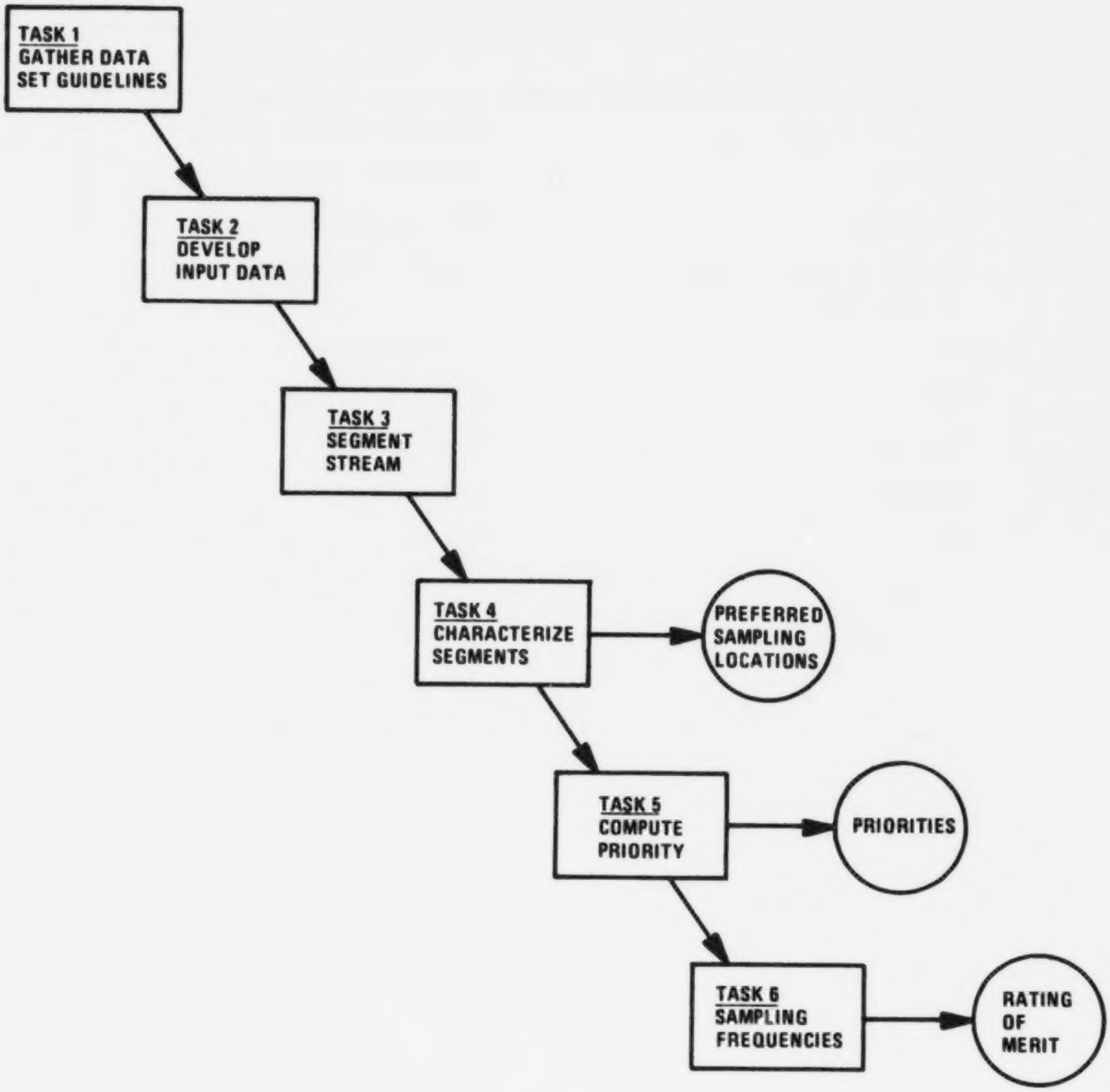


Figure G-1. Handbook Task Flow Diagram

Table G-1. Parameter Model Characterization

Parameter	Characterization
Dissolved Oxygen	Coupled, Non-conservative
Coliforms	Non-conservative
Temperature	Non-conservative
Nitrogen (organic, ammonia, nitrite, nitrate)	Coupled, Non-conservative
pH	Non-conservative
Radioactivity	Non-conservative
Cyanides	Non-conservative
Phosphates	Non-conservative
Chloride	Conservative
Sulphate	Conservative
Heavy metals	Conservative
Fluorides	Conservative
Phenols	Non-conservative
$CaCO_3$ (hardness)	Non-conservative
Sludge	Non-conservative
Color	Non-conservative
Turbidity	Non-conservative
Taste	Non-conservative
Odor	Non-conservative
Petrochemicals	Non-conservative
Foaming materials	Non-conservative

system of units throughout. The system used is the metric system (specifically, the CGS system). It is recognized that this system does not always reflect common practice and tables have been provided for rapid conversion from more common units.

Longitudinal dimensions are measured in two ways in the procedure. For initial location of major features of the stream, the traditional river mile system is used. The river mile system measures all distances upstream from the mouth of the river. For computation purposes, attention may be focused on individual stretches of the river basin. Under these circumstances, distances (symbolized by an "x", frequently with a subscript) are measured downstream from the upstream end of the river segment. It will become clear to the user which system is being used by the context of usage.

Data Inputs

The procedures contained in this handbook assume a relatively low level of information on the historical quality of the river basin. The user should make every effort to employ the best data available in his design. Should the handbook procedures appear incompatible with the existing data the user may be guided by reference to the development contained in Section VI of this report.

TASK 1

COLLECTION OF PERTINENT DATA AND DETERMINATION OF SYSTEM DESIGN GUIDELINES

The initial task in surveillance system design of a river basin involves collection of various pertinent data on the basin and setting up system design guidelines based on the data. The activities in this task should be performed in sequential order as described in Figure G-2.

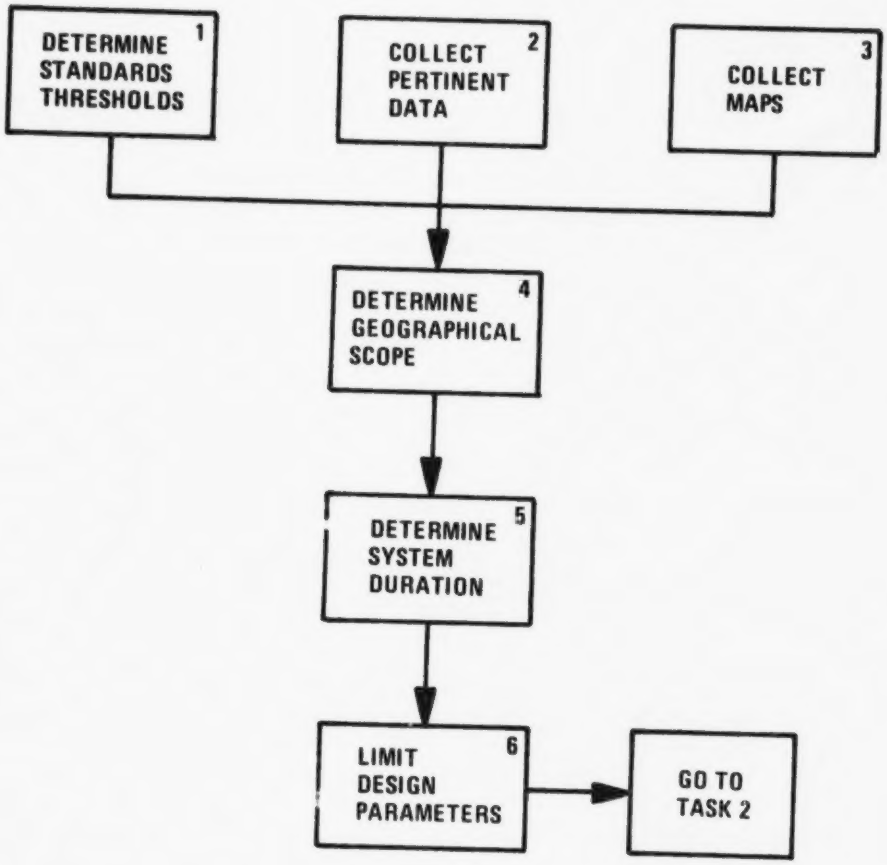

DETERMINE STANDARDS THRESHOLDS
1
COLLECT PERTINENT DATA
2
COLLECT MAPS
3
DETERMINE GEOGRAPHICAL SCOPE
4
DETERMINE SYSTEM DURATION
5
LIMIT DESIGN PARAMETERS
6
GO TO TASK 2

Figure G-2. Task 1 Activity Flow Diagram

TASK 1, ACTIVITY 1— DETERMINE STANDARD THRESHOLDS

Objective

Determine the specific threshold level at which a violation is considered to have occurred. This must be done for each parameter of interest to the designer.

Output

- Index of standard thresholds by parameter and geographical region of applicability.

Information Source

- EPA— Technical Assistance Branch of Office of Water Programs has state-federal water quality standards.
- Individual States— The most up-to-date standards are available directly from the states.

Procedure

- Obtain from the listed information sources all parameter water quality standards for the basin.
- From these standards define a standards threshold for each parameter included in the documents and for all sections of the river. Or, if no standard exists for the parameter of interest, select an arbitrary threshold.
- Go to Task 1, Activity 2

TASK 1, ACTIVITY 2— COLLECT PERTINENT DATA

Objective

The objective of this activity is to bring together and organize the data required for surveillance system preliminary design.

Output

- Index of all water quality stations and locations in the river basin
- Index of all U.S. Geological Survey stream flow gauging stations and their locations on the river basin

- Index of municipal and regional sanitary outfalls and their locations
- Index of industrial waste outfalls, their locations, and SIC codes.

Information Sources

- EPA—STORET inventory, municipal waste inventory, industrial implementation data.
- U.S. Geological Survey—"Water Resources data for (state)," Parts 1 and 2; detailed data on stream flow cross-sections (Form 9-207) from regional offices.
- U.S. Army Corps of Engineers—"Refuse Act Permit Program" data from regional offices.
- State Agencies
- Local Agencies
- Universities

Procedure

- Obtain a STORET Statistical Summary retrieval for all parameters of interest to the designer, from all stations of the river basin, over a period of at least two years.
- Obtain the "Water Resources Data for (state)," from U.S. Geological Survey over the same time period as the retrieval of STORET, for all USGS stations on the basin.
- Obtain the "Form 9-207" data from the U.S. Geological Survey basin regional office for stations of the basin.
- Obtain Industrial and Municipal Effluent data from STORET for the entire river basin.
- Obtain any additional, federal, state or local inventoried data which may be available.
- Index these data in a form which may be easily accessed.
- Go to Task 1, Activity 3.

TASK 1, ACTIVITY 3—MAP COLLECTION

Objective

The objective of this activity is to provide the preliminary design program with the appropriate base material for consideration of geographical relationships.

Output

- An overall basin map with river mileage reference points, and, if available, a complete set of detailed maps for the river basin.

Information Sources

- EPA— The Surveillance Branch maintains a complete aperture card file of U.S. Geological Survey 15' quadrangle maps.
- U.S. Geological Survey— Topographic maps— 7-1/2', 15' and 30' (1:250,00) maps available without woodlands overprint. Also frequently available as special printings, without contours.
- NOAA-NOS— Coastal navigation charts (including charts of tidal rivers such as the Hudson River), Great Lake navigation charts, Aeronautical charts.
- U.S. Army Corps of Engineers— Navigational charts of inland rivers.

Procedure

- Derive an overall basin map which is most convenient for the user.
- If river mileages are not available on the map at hand, use STORET data giving river mileages and mark these data points as milestones with the appropriate river mile. The river miles between milestones may be approximated with a Map and Blueprint Measure (for example, Charrette Catalogue No. 4719, Charrette Co., New York, N.Y., 1971).
- Go to Task 1, Activity 4.

TASK 1, ACTIVITY 4— DETERMINE GEOGRAPHICAL SCOPE

Objective

Identify the extent of the river basin to be included in the surveillance system design ("BASIN SUBSET"), and prepare a "situation map" of this basin subset.

Output

- "Situation Map" of the basin subset.

Inputs

- Task 1, Activity 2

Discussion

It may be desirable to limit the extent of the streams considered in design to a portion of the river basin. Reasons for exclusion from the basin subset are:

1) Arbitrary exclusion for reasons external to the preliminary design process
2) Any tributary which has no effluent sources on it will be excluded.

Procedure

- On the overall basin map, define those streams to be included in the basin subset.
- Prepare (for example, by tracing) a map of the basin subset.
- On this map ("situation map") mark all effluent source points and tributary input points on the basin subset.
- Mark all points on the basin subset where stream flow data is available from U.S. Geological Survey.
- Go to Task 1, Activity 5.

TASK 1, ACTIVITY 5— IDENTIFY SYSTEM DURATION

Objective

Specify the duration in which surveillance system design factors are to be computed.

Output

- System duration (days).

Inputs

- Data from Task 1, Activity 2
- Decision based on factors external to this procedure.

Discussion

System duration is that period of time which the designer anticipates that the configuration of the surveillance system will remain fixed. Although it is called a duration, it is important to determine the time of year as well, when the system duration is less than one year.

Procedure

- Using judgment based upon a knowledge of the external constraints, identify the system duration. All the data used in this procedure must be based on averages over the system duration identified in this activity.
- Go to Task 1, Activity 6.

TASK 1, ACTIVITY 6— LIMIT PARAMETERS TO BE USED IN SYSTEM DESIGN

Objective

Specify which of the parameters of interest may be used in surveillance system design.

Output

- Design parameters names and units.

Inputs

- Task 1, Activity 1
- Task 1, Activity 2
- Task 1, Activity 5.

Procedure

- Identify all water quality parameters which are included in the regional stream standards.
- Identify those parameters of interest for which there is data meeting the following criteria:
    1) concentration data in some form for each effluent outfall. (General textbook data may be sufficient.)
    2) at least two measurements of that parameter in the stream during the system duration at most of the STORET stations.
- Identify which parameters may be of particular interest in surveillance system design due to their high risk in violating the standards.
- Specify the parameters selected for surveillance system design.
- Go to Task 2.

TASK 2

CATALOGING AND CONVERSION OF INPUT DATA

In this task pertinent input data will be selected, based on its quality, and converted to a form which is directly usable in the procedure. The activities in this task should be performed in sequential order, as shown in Figure G-3.

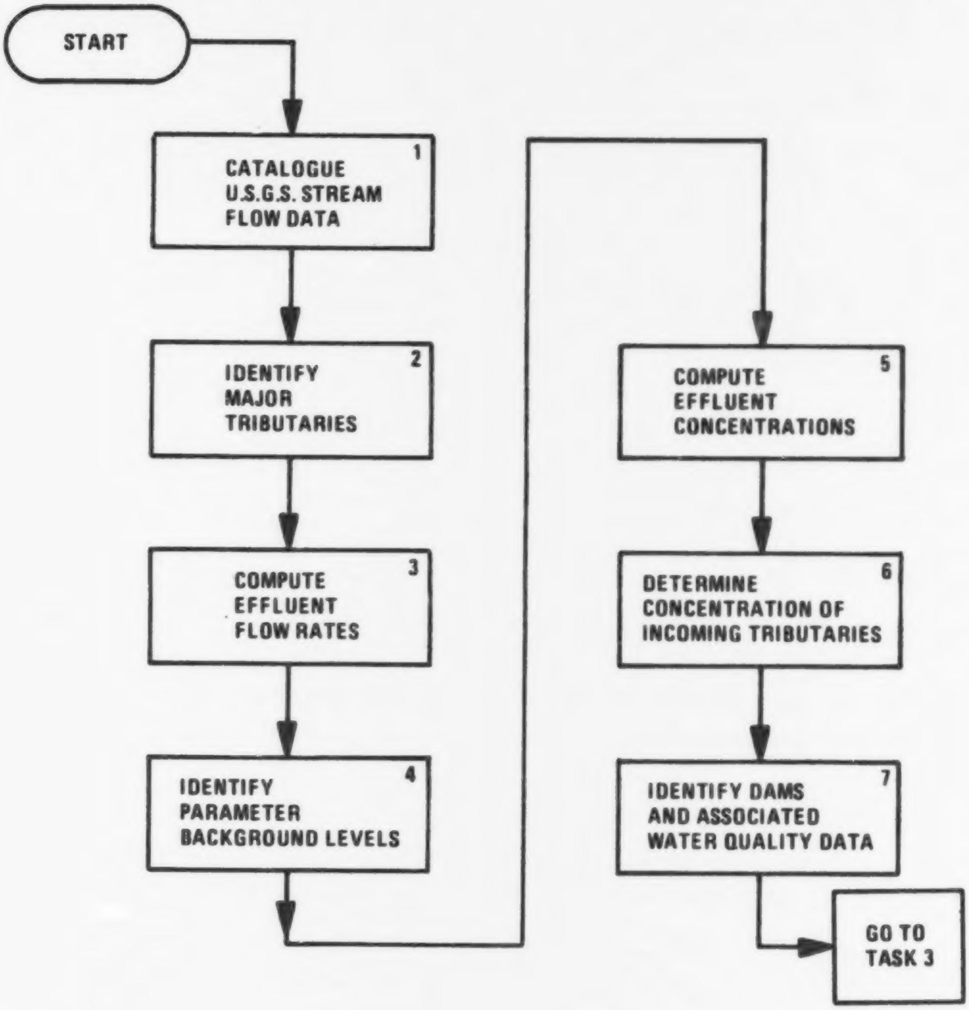

START
1
CATALOGUE U.S.G.S. STREAM FLOW DATA
2
IDENTIFY MAJOR TRIBUTARIES
3
COMPUTE EFFLUENT FLOW RATES
4
IDENTIFY PARAMETER BACKGROUND LEVELS
5
COMPUTE EFFLUENT CONCENTRATIONS
6
DETERMINE CONCENTRATION OF INCOMING TRIBUTARIES
7
IDENTIFY DAMS AND ASSOCIATED WATER QUALITY DATA
GO TO TASK 3

Figure G-3. Task 2 Activity Flow Diagram

TASK 2, ACTIVITY 1—CATALOGUE GEOLOGICAL SURVEY STREAM FLOW DATA

Objective

Find stream velocity, depth, stream flow and temperature during the specified system duration at all available stations in the basin subset.

Output

- Stream velocity (U), depth (H), stream flow (Q) and temperature.

Inputs

- Task 1, Activity 2: U.S. Geologic Survey Intensive Studies (Form 9-207)
- Task 1, Activity 5: system duration.

Procedure

Perform the following tasks for each station using the U.S. Geological Survey Form 9-207, identify all measurements within the system duration specified in Task 1, Activity 5. Use at least two years of data.

- Using the identified measurements compute the average flow velocity over the system duration.
- Compute average depth $(H) = \frac{\text{cross sectional area}}{\text{width}}$ over the system duration.
- Compute average stream flow over the system duration.
- Compute average temperature over the system duration.
- Check the "situation map" to see if all stream flow data points are properly located.
- Go to Task 2, Activity 2.

TASK 2, ACTIVITY 2—IDENTIFY MAJOR TRIBUTARIES

Objective

Find flow rates of all tributaries of the basin subset and select the major tributaries.

Outputs

- Tributary flow rates in liters/second
- List of major tributaries.

Inputs

- Task 1, Activity 2
- Tributary drainage area from maps.

Discussion

This activity is to be performed on all tributaries which flow directly into the basin subset.

Procedure

The logic shown in Figure G-4 is used in treating each tributary to the basin subset.

TASK 2, ACTIVITY 3—COMPUTE EFFLUENT FLOW RATES

Objective

Select the most reliable data available for each effluent outfall in the basin subset and convert effluent flow rates, Q_s, to liters/sec.

Output

- Effluent flow rates (liters/sec).

Input

- Task 1, Activity 2.

Procedure

- For each outfall identify the most reliable data from the following sources:
  1) Refuse act permit program data
  2) STORET data
  3) State and local data
- Convert this data to liters/sec using Table G-2.
- Go to Task 2, Activity 4.

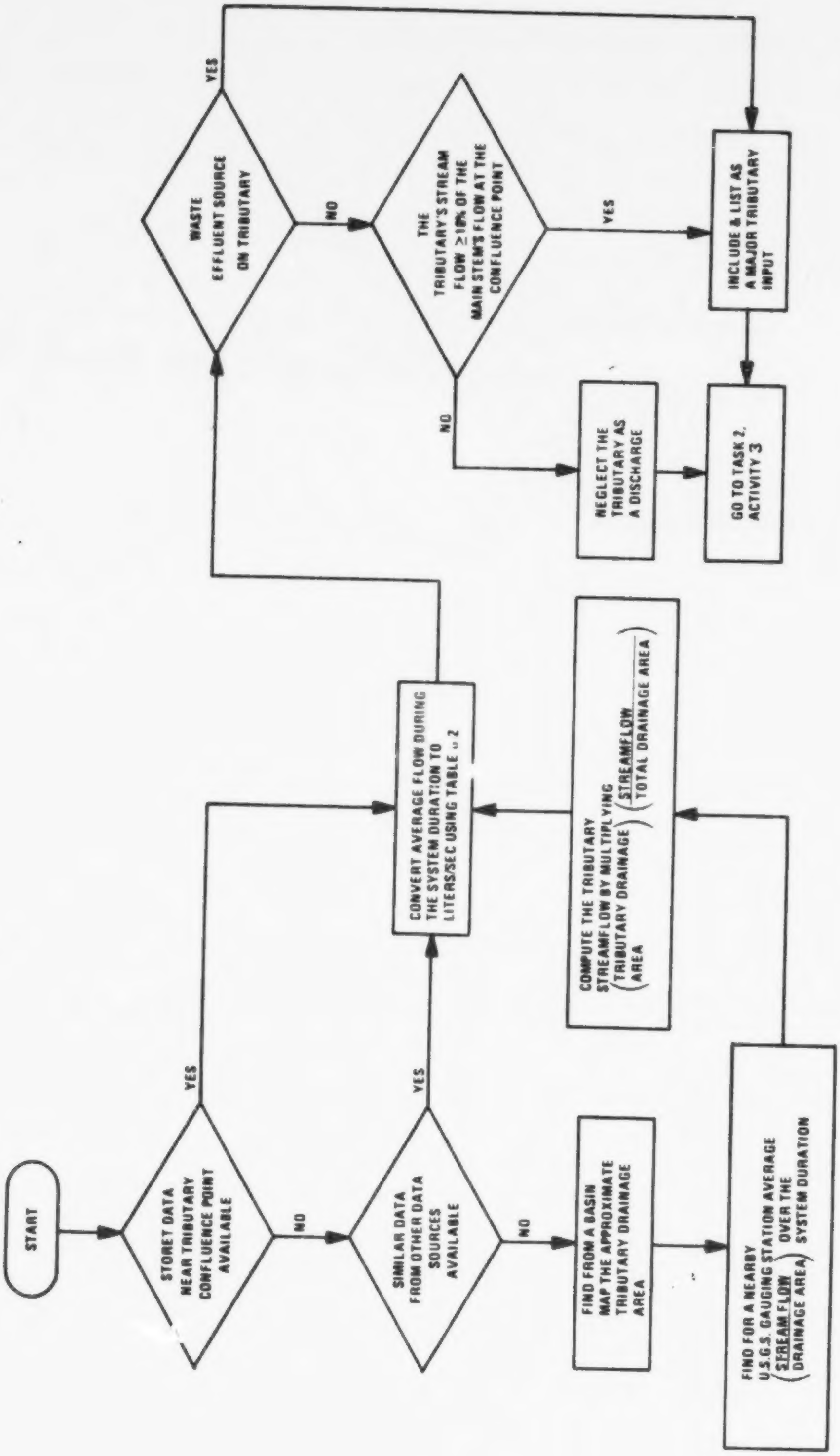

START
STORET DATA NEAR TRIBUTARY CONFLUENCE POINT AVAILABLE
YES
NO
SIMILAR DATA FROM OTHER DATA SOURCES AVAILABLE
YES
NO
FIND FROM A BASIN MAP THE APPROXIMATE TRIBUTARY DRAINAGE AREA
FIND FOR A NEARBY U.S.G.S. GAUGING STATION AVERAGE (STREAM FLOW / DRAINAGE AREA) OVER THE SYSTEM DURATION
COMPUTE THE TRIBUTARY STREAMFLOW BY MULTIPLYING (TRIBUTARY DRAINAGE AREA) (STREAMFLOW / TOTAL DRAINAGE AREA)
CONVERT AVERAGE FLOW DURING THE SYSTEM DURATION TO LITERS/SEC USING TABLE G-2
WASTE EFFLUENT SOURCE ON TRIBUTARY
YES
NO
THE TRIBUTARY'S STREAM FLOW ≥10% OF THE MAIN STEM'S FLOW AT THE CONFLUENCE POINT
YES
NO
INCLUDE & LIST AS A MAJOR TRIBUTARY INPUT
NEGLECT THE TRIBUTARY AS A DISCHARGE
GO TO TASK 2, ACTIVITY 3

Figure G-4. Logic Flow for Task 2, Activity 2

Table G-2. Conversion Factors for Flow

Input Data Units	ft^3/sec	gal x 10^6/day	$meters^3$/sec	gal/day
Multiply data number by the following to give units (liters/sec).	28.33	43.80	1×10^{-3}	4.38×10^{-5}

TASK 2, ACTIVITY 4—DETERMINE BACKGROUND LEVEL OF EACH DESIGN PARAMETER

Objective

For each of the design parameters, identify the characteristic background concentration for the basin subset (C_{bk} (I)).

Output

Background levels in units defined in Task 1, Activity 6.

Inputs

- Task 1, Activity 2: Historical Water Quality Data
- Task 1, Activity 6: Design Parameters.

Procedure

- Determine the background concentrations for each design parameter. For DO and total coliforms, the value may be determined from Table G-3. For all parameters including DO and coliform, a more general approach is to use STORET data and:
  1) Determine the lowest values of parameter concentration found within the basin subset.
  2) Check to see if the value may be associated with a source.
  3) If not associated with a source, let the background concentration C_{bk} (I) equal that value.
  4) If associated with a source, let C_{bk} (I) = 0.
- Go to Task 2, Activity 5.

Table G-3. Background Parameter Concentrations

Range	Region	D.O. Deficit (mg/1) (D_{bk})	Coliforms (MPN/100 ml)
Low	Sparse Vegetation	0.5	10
Moderate	Grass, Woodlands	1.0	100
High	Organic, Swampy Areas	2.0	1,000

Source: Simplified Mathematical Modeling of Water Quality,
Report to Environmental Protection Agency, March 1971

TASK 2, ACTIVITY 5—DETERMINE THE PARAMETER CONCENTRATIONS AND FLOWS OF EACH EFFLUENT

Objective

For each design parameter and each effluent outfall, determine the parameter concentration and the flow of the effluent.

Output

- Parameter concentrations in units defined in Task 1, Activity 6.
- Effluent flow in liters/sec.

Inputs

- Task 1, Activity 1
- Task 1, Activity 2
- Task 1, Activity 6
- Task 2, Activity 4.

Discussion

For dissolved oxygen both BOD and DO concentrations are needed. For other parameters only the concentration of the parameters themselves are needed. The units of the concentrations should be consistent with the units established in Task 1, Activity 6.

Procedure

The analysis is performed as shown in Figure G-5 for all parameters, except DO (Figure G-5 applies to the BOD case). Figure G-5 references use of Table G-4. If effluent data are not available, either of two methods can be used: one for industrial effluents and one for municipal treatment plant effluents.

- Method 1: For industrial sources, it may be possible to estimate effluent concentrations based on standard textbook data. Recommended sources for such information are:

  1) Eckenfelder, W. W., Water Quality Engineering for Practicing Engineers, Barnes & Noble, New York, 1970.
  2) Eckenfelder, J. R., Industrial Water Pollution Control, McGraw-Hill, New York, 1966.
  3) Lund, H. F., Industrial Pollution Control Handbook, McGraw-Hill, New York.
  4) Nemerow, N. L., Theories and Practices of Industrial Waste Treatment, Addison-Wesley, Boston, 1963.

Table G-4. Conversion Factors for Concentration

Input Data Units	gm liter	Pounds Gallon	Pounds liter	Pounds Million Gals.	Parts Per Million (ppm)
Multiply Data by the following to give units mg/l	.001	1.2×10^5	4.54×10^5	1.2×10^2	1

- Method 2: For municipal waste water treatment, the following estimation technique, modified from Simplified Mathematical Modeling of Water Quality (Environmental Protection Agency, 1971)

  $$Q_s = f_5 \; P_0 \quad \text{l/sec}$$

  $$L_s = \frac{f_4 \cdot f_3 \cdot f_1 \cdot P_0}{Q_s} \quad \text{mg/l}$$

  where the f-factors may be obtained from Tables G-5, G-6 and G-7, and P_0 is the present population of the municipality.

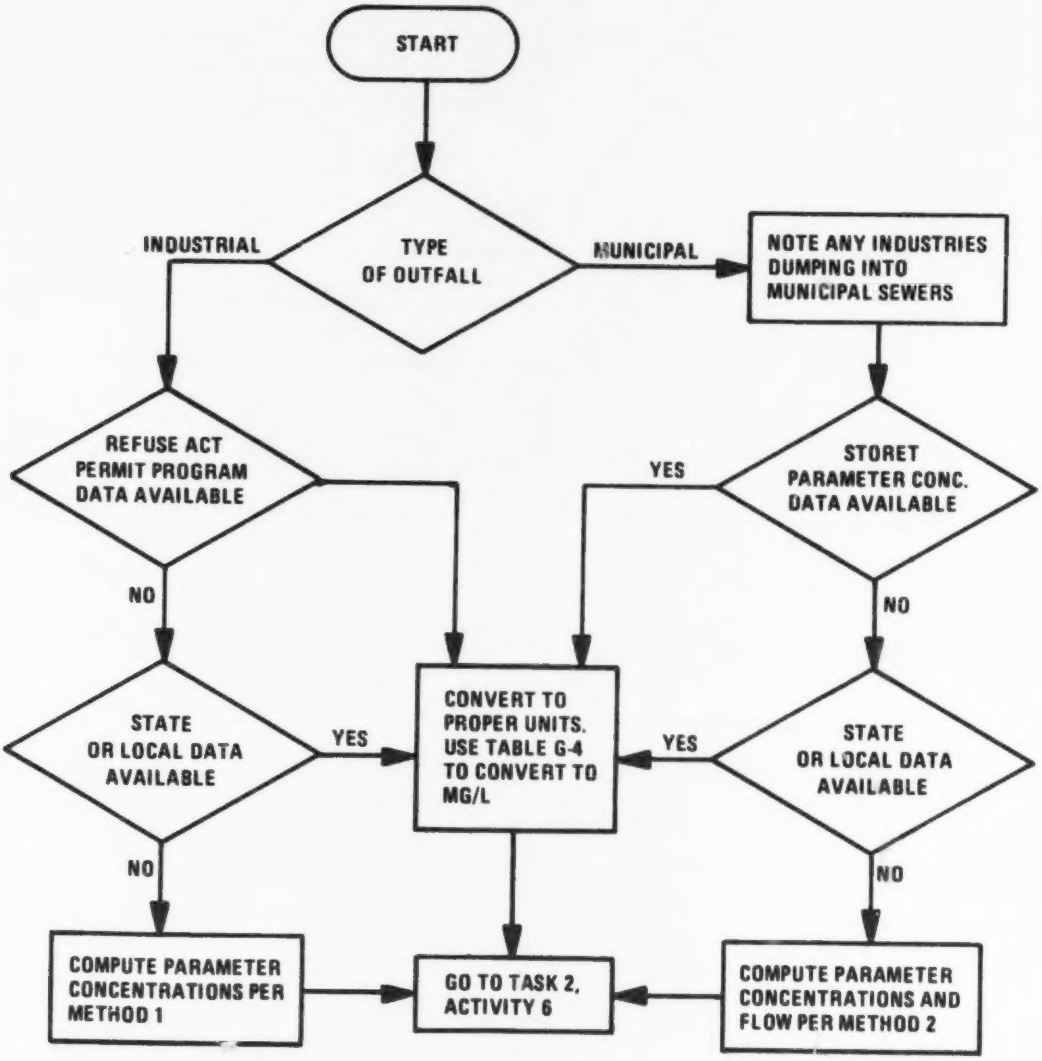

START
TYPE OF OUTFALL
INDUSTRIAL
MUNICIPAL
NOTE ANY INDUSTRIES DUMPING INTO MUNICIPAL SEWERS
REFUSE ACT PERMIT PROGRAM DATA AVAILABLE
YES
STORET PARAMETER CONC. DATA AVAILABLE
NO
NO
STATE OR LOCAL DATA AVAILABLE
YES
CONVERT TO PROPER UNITS. USE TABLE G-4 TO CONVERT TO MG/L
YES
STATE OR LOCAL DATA AVAILABLE
NO
NO
COMPUTE PARAMETER CONCENTRATIONS PER METHOD 1
GO TO TASK 2, ACTIVITY 6
COMPUTE PARAMETER CONCENTRATIONS AND FLOW PER METHOD 2

Figure G-5. Logic Flow for Task 2, Activity 5 for all Cases Except DO

Table G-5. Population Growth Factors (f_1)

Area Growth Description	Growth Factor (f_1)	Increase Range
Established Static	1.10	0 - 25
Low to Moderate	1.50	25 - 75
Moderate to High	2.00	75 - 125
Rapidly Developing	2.50	125 - 375

Table G-6. Per Capita Waste Flow (f_5) and Quantities (f_3)

	Flow $\left(\frac{\text{liters}}{\text{Cap-sec}} \times 10^3\right)$	Ultimate BOD $\left(\frac{\text{mg}}{\text{Cap-sec}}\right)$		Solids $\left(\frac{\text{mg}}{\text{Cap-sec}}\right)$	Nutrients $\left(\frac{\text{mg}}{\text{Cap-sec}}\right)$		Coliforms $\left(\frac{\text{MPN}}{\text{Cap-sec}} \times 10^3\right)$
		C	N		N	P	
Low	4.4	0.63	0.37	0.79	0.079	0.016	58
Average	7.8	1.32	0.79	1.58	0.184	0.031	116
High	13.1	2.10	1.47	2.63	0.290	0.053	174

Table G-7. Estimated Efficiency of Treatment Levels on Carbonaceous BOD (f_4)

Treatment Level	% Removal	#/Capita/BOD Remaining	f_4 fraction BOD Remaining
Primary Treatment	50	0.125	0.50
Marginal Secondary Treatment	70	0.075	0.56
High Rate Biological Treatment	85	0.037	0.44
Secondary Treatment with Nitrification	90	0.025	0.12
Advanced Treatment	95	0.013	0.5
Ultimate Treatment	99	0.025	0.1

For DO, Figure G-6 gives the logical analysis. Another method of evaluation may be required in the DO analysis:

- Method: For DO in the case of industrial flushing water, obtain the average concentration of dissolved oxygen from the nearest upstream set of historical data (C(DO)). Then assume the effluent source concentration C_s(DO) is equal to C(DO).

TASK 2, ACTIVITY 6—DETERMINE PARAMETER CONCENTRATION OF EACH INCOMING TRIBUTARY

Objective

Find the concentrations of each design parameter at the points where major tributaries flow into the basin subset.

Output

- Parameter concentrations in appropriate units.

Inputs

- Task 1, Activity 2—Pertinent Data
- Task 1, Activity 6—Design Parameters
- Task 2, Activity 2—Tributary Identification
- Task 2, Activity 4—Background Levels.

Discussion

If historical data is used it should be obtained from a point as close to the tributary mainstem confluence point as possible, still being on the tributary and the background level for that parameter should be subtracted from historical data concentrations.

Procedure

Perform the logic in Figure G-8 to compute the concentrations of each design parameter at the confluence points of major tributaries with the basin subset.

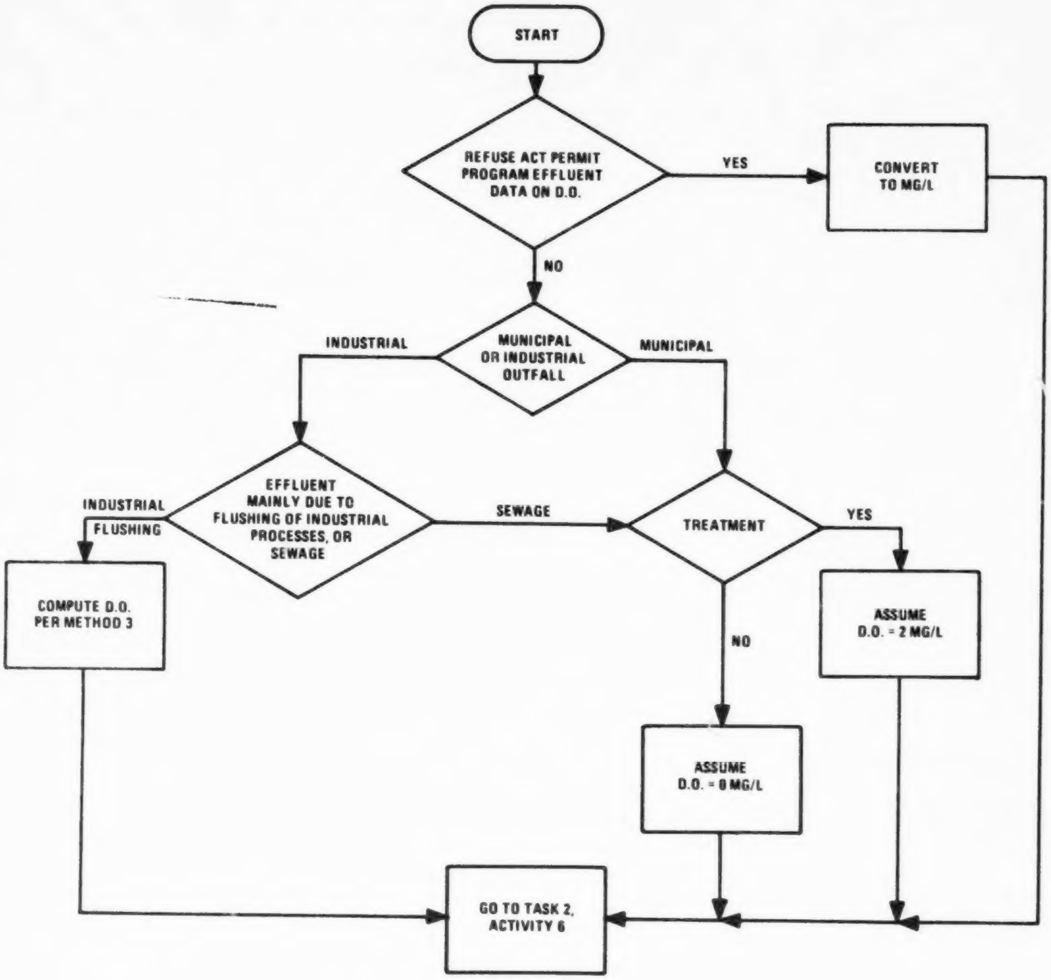

START
REFUSE ACT PERMIT PROGRAM EFFLUENT DATA ON D.O.
YES
CONVERT TO MG/L
NO
INDUSTRIAL
MUNICIPAL OR INDUSTRIAL OUTFALL
MUNICIPAL
INDUSTRIAL FLUSHING
EFFLUENT MAINLY DUE TO FLUSHING OF INDUSTRIAL PROCESSES, OR SEWAGE
SEWAGE
TREATMENT
YES
COMPUTE D.O. PER METHOD 3
ASSUME D.O. = 2 MG/L
NO
ASSUME D.O. = 0 MG/L
GO TO TASK 2, ACTIVITY 6

Figure G-6. Logic Flow for Task 2, Activity 5, DO Case

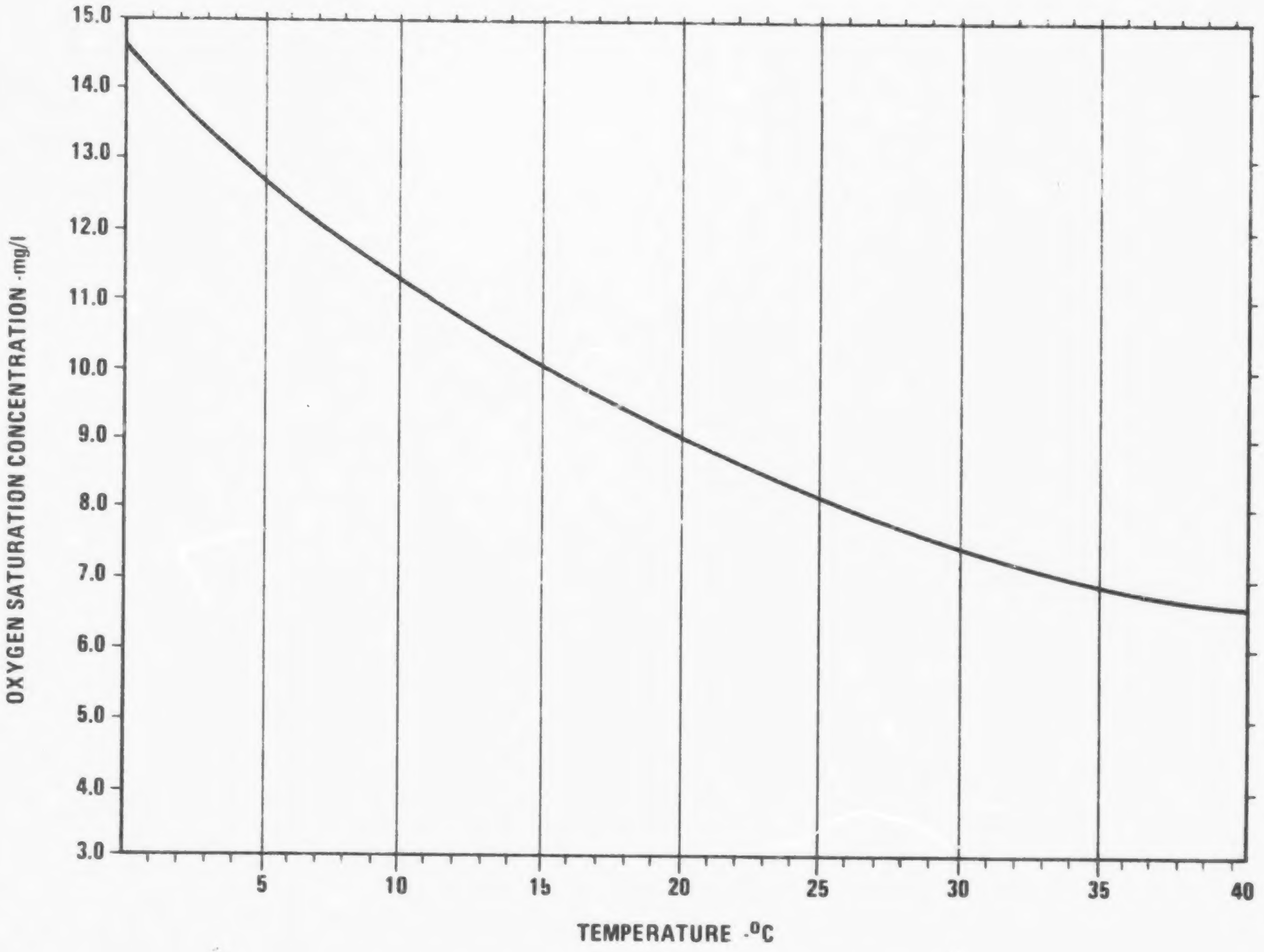


Figure G-7. Saturation–Temperature Relationship in Fresh Waters

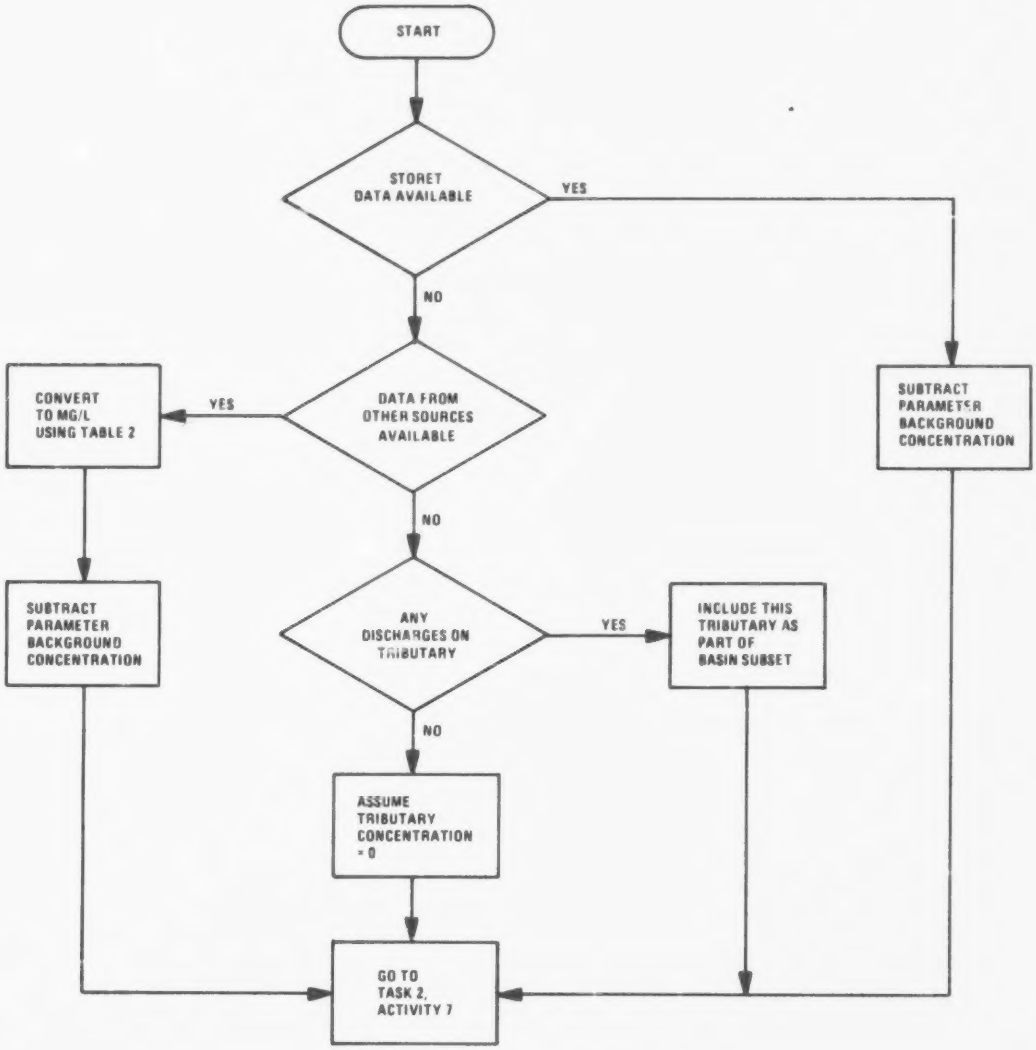

START
STORET DATA AVAILABLE
YES
NO
DATA FROM OTHER SOURCES AVAILABLE
YES
CONVERT TO MG/L USING TABLE 2
NO
SUBTRACT PARAMETER BACKGROUND CONCENTRATION
ANY DISCHARGES ON TRIBUTARY
YES
INCLUDE THIS TRIBUTARY AS PART OF BASIN SUBSET
NO
ASSUME TRIBUTARY CONCENTRATION = 0
SUBTRACT PARAMETER BACKGROUND CONCENTRATION
GO TO TASK 2, ACTIVITY 7

Figure G-8. Logic Flow for Task 2, Activity 6

TASK 2, ACTIVITY 7—IDENTIFY DAMS AND ASSOCIATED WATER QUALITY DATA

Objective

Identify all reservoirs on the Basin Subset and obtain flow and design parameter concentration data from the nearest stations below their respective dams.

Output

- Dam outflow and concentration data.

Inputs

- Task 1, Activity 2—Field Data
- Task 1, Activity 4—Situation Map
- Task 1, Activity 6—Design Parameters.

Procedure

- Identify all reservoirs on the situation map.
- Identify the nearest field data station downstream from dam.
- Extract flow and typical design parameter concentrations taken during system duration at this station.
- Convert this data to the appropriate units.
- Go to Task 3.

TASK 3

SEGMENTATION AND COMPUTATION OF SEGMENT INPUT VARIABLES

The procedure for segmenting a river basin consists of a number of activities which must be performed in sequence, beginning at the headwaters of the main-stem and continuing to the river mouth. When a confluence point of a tributary, which must be segmented, is encountered, the activities are again commenced at the headwaters of the tributary until reaching the main stem confluence point. The procedure then continues along the main stem.

After an effluent group is identified as significant and segmentation is performed, a number of variables describing the segment are computed and entered into a computational table. To avoid confusion one computational table should be set up for each parameter. Tables G-8 and G-9 illustrate the typical table formats for BOD-DO and uncoupled parameters. The index letter N is used to identify the segments on the computational table. The index NN is used to indicate when the task is to end. Both of these indexes are initially zero. The logical flow of activities in this task is described in the following flowchart (Figure G-9).

Table G-8. Computation Table No. 1 for BOD-DO

Segment		Segment Position (RMI)		x_{tol}	H	U	Q		C_{sat}	k_a			Q_g	L_g	D_g	k_d	N
Segment Number	Code Number	Upstream End	Downstream End	Tolerance Length (miles)	Stream Depth (ft)	Flow Velocity (ft) (sec)	Stream Flow (liters/sec)	Water Temp (°C)	Saturation (mg/L) DO Concentration	Reaeration (day^{-1}) Rate Coeff.	Discharge Charac. Industry-SIC	Municipal—Treatment Tributary—Name	Group Flow (liters/sec)	Discharge BOD Concentration (mg/l)	Discharge DO (mg/l) Deficit Concen.	Decay Rate (day^{-1}) Coefficient	Segment Sequence Number
1																	1
2																	2
3																	3
4																	4
5																	5
6																	6
7																	7
8																	8
9																	9

Table G-9. Computation Table No. 1 for Uncoupled Parameters

Segment		Segment Position (RMI)		x_{tol}	H	U	Q				Q_g	C_g	k_d	N
Segment Number	Code Number	Upstream End	Downstream End	Tolerance Lgth (miles)	Stream Depth (ft)	Flow Velocity (ft/sec)	Stream Flow (liters/sec)	Water Temp (°C)	Discharge Characteristics Industry—SIC	Municipal-Treatment Tributary—Name	Group Flow (liters/sec)	Discharge Concentration (mg/l)	Decay Rate Coefficient (days^{-1})	Segment Sequence Number
1														1
2														2
3														3
4														4
5														5
6														6
7														7
8														8
9														9

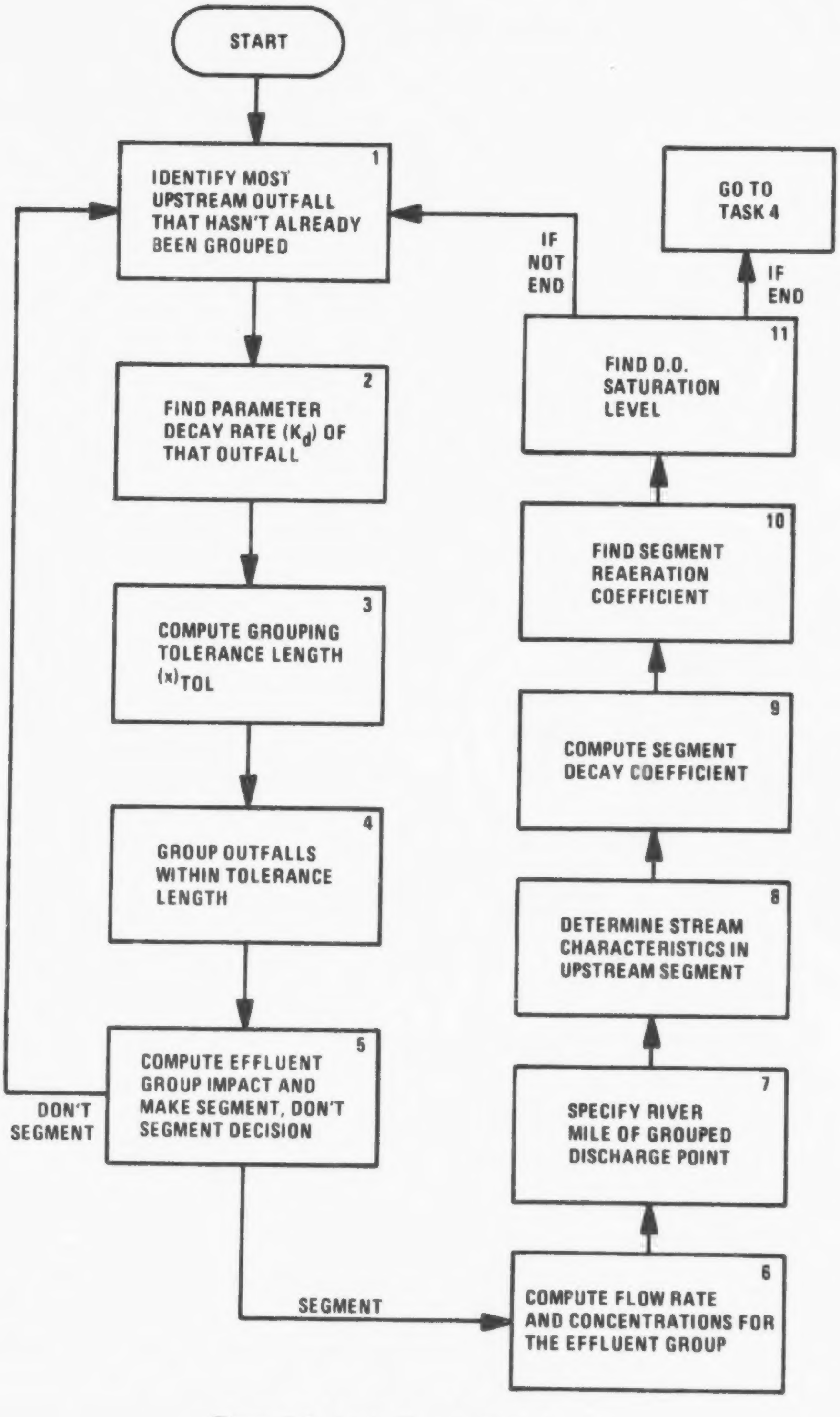

START
1
IDENTIFY MOST UPSTREAM OUTFALL THAT HASN'T ALREADY BEEN GROUPED
2
FIND PARAMETER DECAY RATE (K_d) OF THAT OUTFALL
3
COMPUTE GROUPING TOLERANCE LENGTH $(x)_{TOL}$
4
GROUP OUTFALLS WITHIN TOLERANCE LENGTH
5
COMPUTE EFFLUENT GROUP IMPACT AND MAKE SEGMENT, DON'T SEGMENT DECISION
DON'T SEGMENT
SEGMENT
6
COMPUTE FLOW RATE AND CONCENTRATIONS FOR THE EFFLUENT GROUP
7
SPECIFY RIVER MILE OF GROUPED DISCHARGE POINT
8
DETERMINE STREAM CHARACTERISTICS IN UPSTREAM SEGMENT
9
COMPUTE SEGMENT DECAY COEFFICIENT
10
FIND SEGMENT REAERATION COEFFICIENT
11
FIND D.O. SATURATION LEVEL
IF NOT END
IF END
GO TO TASK 4

Figure G-9. Logic Flow for Task 3

TASK 3, ACTIVITY 1—IDENTIFY MOST UPSTREAM OUTFALL

Objective

Find, using the situation map, the most upstream effluent outfall or major tributary input which has not already been grouped in Task 3, Activity 4.

Output

- Discharge (effluent outfall or tributary) identification.

Inputs

- Task 1, Activity 4—Situation Map
- Task 2, Activity 7—Reservoir identification
- Task 3, Activity 4—Grouping

Procedure

- In the initial pass through this loop identify the outfall which is furthest upstream on the main stem (primary stream). If there is a tributary whose confluence point is above any outfalls on the main stem, and which contains an outfall, start segmentation at this outfall, on this "uppermost" tributary which contains an outfall.
- If this activity is entered from Task 3, Activities 5 or 11 identify the next discharge downstream from the previously considered discharge group. If the point of confluence with a tributary in the basin subset is reached, identify the outfall furthest upstream on the tributary and begin segmentation of the tributary at this outfall.
- If a reservoir is encountered before the next outfall or tributary ignore the stretch of reservoir by

  a) ending the upstream segment at the top end of the reservoir.
  b) beginning the next segment at the dam.
- If there are any other major changes in physical characteristics, break the river into "subsegments" for more accurate computation of the stream profile. The stream characteristics and reaeration coefficients must be specified for these "subsegments," however they are not to be rated themselves since they do not represent independent pollution threats.
- If the lower end of the main stem is reached let NN = 1, and go to Task 3, Activity 8; if not, go to Activity 2.

TASK 3, ACTIVITY 2—FIND OUTFALL k_d VALUE

Objective

Find a length decay coefficient which corresponds to the outfall identified in Task 3, Activity 1.

Output

- k_d, in days^{-1}, for the outfall, and for each design parameter at the outfall.

Inputs

- Task 1, Activity 2—Stream data.
- Task 2, Activity 1—Stream flow data.

Discussion

The decay coefficients of all design parameters must be found and compared in this activity. All conservative substances such as fluorides have decay coefficient k_d of zero, by definition. In the case of coupled BOD-DO, the decay coefficient of BOD is used in determining the length scale. From Fair, Geyer, and Okun the following BOD k_d values are assumed.

Stream depth greater than 10 feet	Municipal Effluent (No Treatment). Industrial Effluent.	$k_d = .4$
	Municipal Effluent (Primary Treatment)	$k_d = .35$
	Municipal Effluent (Secondary Treatment)	$k_d = .2$

Procedure

- Identify the effluent discharge type for that outfall described in Task 3, Activity 1.
- Find the decay coefficients, k_d, for all design parameters. To do this for BOD:

  1) Find $k_{d\ \text{depth} = 10\ \text{feet}}$ using the appropriate assumption above and identify the corresponding line of Figure G-10.
  2) Follow this line laterally until appropriate depth is reached on abscissa.
  3) Read the corresponding k_d value on the ordinate.

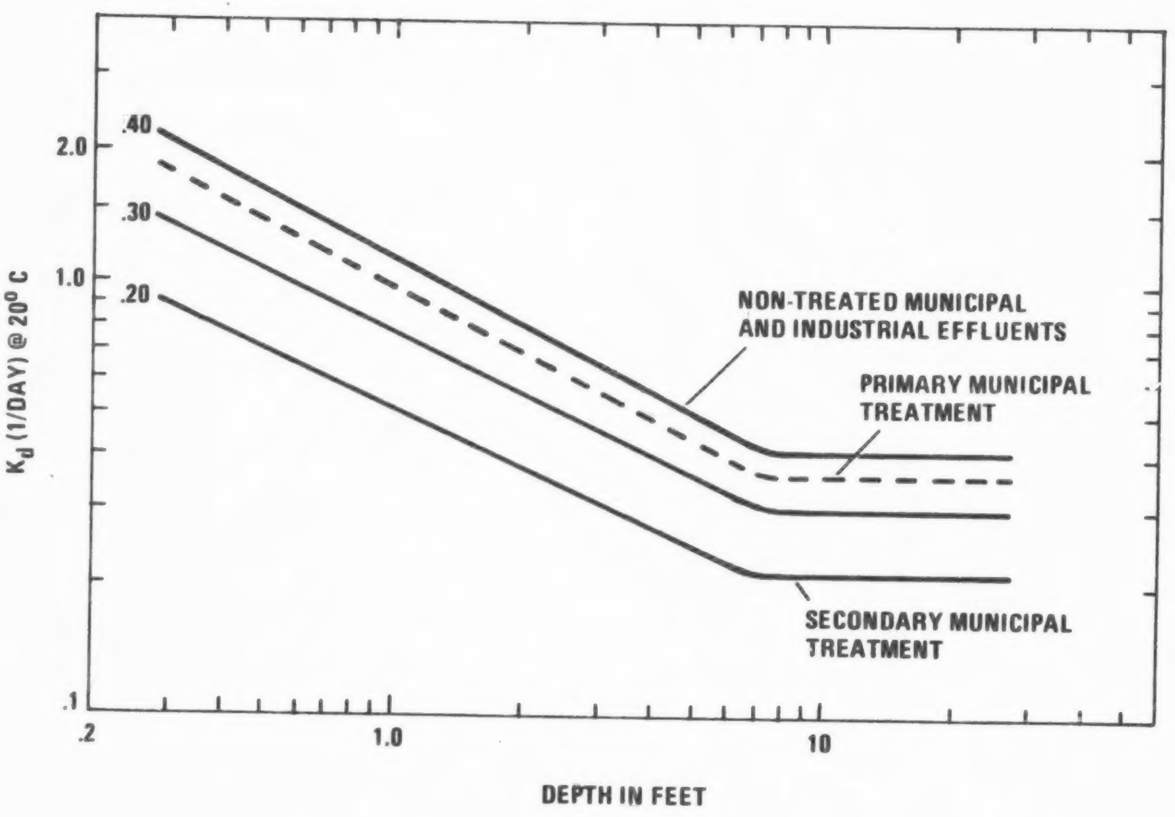


Figure G-10 Deoxygenation Coefficient (k_d) as a Function of Depth

- If general text information on a certain decay coefficient of the parameter is not available but concentrations at two locations, x_1 and x_2, are known and it can be assumed that there are no discharges between x_1 and x_2, the compute:

$$k_d = \frac{U}{(x_2 - x_1)} \ln \frac{C(x_1)}{C(x_2)}$$

where U = stream flow velocity at the nearest U.S.G.S. station

$C(x_1)$ = parameter concentration at x_1

$C(x_2)$ = parameter concentration at $x_2 > x_1$.

- Specify the highest k_d value of the design parameters and assign that k_d to the outfall.
- Go to Activity 3.

TASK 3, ACTIVITY 3—COMPUTE GROUP TOLERANCE LENGTH

Objective

Compute the distance (x_{tol}) from the effluent outfall identified in Task 3, Activity 1, within which other outfalls may be "lumped" together with it and considered one outfall.

Output

- x_{tol} in miles.

Inputs

- Task 3, Activity 2—Outfall decay coefficient k_d
- Task 2, Activity 1—Stream velocity (U).

Discussion

The tolerance length is defined as the distance from the effluent source in which 10% of the parameter with the highest k_d has decayed.

With this definition,

$$x_{tol} = \frac{(1.72)^* U}{k_d} \text{ miles}$$

Procedure

- Locate the nearest U.S.G.S stream flow station from the discharge identified in Task 3, Activity 1, and find its flow velocity (U).
- Compute x_{tol}.
- Go to Activity 4.

TASK 3, ACTIVITY 4—GROUP OUTFALLS WITHIN TOLERANCE LENGTH

Objective

Group all discharges lying within x_{tol} of the discharge identified in Task 3 Activity 1.

Output

- Discharge Grouping

Inputs

- Task 1, Activity 4—Situation map
- Task 3, Activity 3—Tolerance length (x_{tol}).

Procedure

- Locate all other discharges along stream which fall within x_{tol} distance of the discharge identified in Task 3, Activity 3.
- If a reservoir is encountered within x_{tol} treat as that given in Task 3, Activity 1, procedure step 3.
- Go to Activity 5.

TASK 3, ACTIVITY 5—COMPUTE EFFLUENT GROUP IMPACT AND MAKE INCLUDE/DON'T INCLUDE DECISION

Objective

Compute the summed impact of the group of outfalls identified in Task 3 Activity 4 and decide whether to neglect this impact or include it in priority rating.

Output

- Include/Don't Include Decision.

Inputs

- Task 2, Activity 2—Tributary flow rates
- Task 2, Activity 3—Effluent flow rates
- Task 2, Activity 5—Effluent concentrations
- Task 2, Activity 6—Tributary concentrations

Procedure

Perform the following steps for each parameter

- For each source in the group, compute the mass loads

  $$W_s\ (I) = Q_s * (C_s)$$

  where: I = parameter identifier

  C_s = parameter concentration of the source.

- Compute the sum of mass loads, for all sources in the group

  $$W_g\ (I) = \sum_s W_s\ (I)$$

- Compute the total impact of the effluent group (Impact (I)), on the stream concentration.

  $$\text{Impact } (I) = \frac{W_g(I)}{Q}$$

where Q = approximate average flow during system duration from nearby U.S.G.S. station.

- Decide at what threshold $T(I)$ the impact should be considered negligible. (As a guideline, for this study a 0.1 mg/l impact change of DO or BOD is set as the threshold.)
- If Impact (I) is less than or equal to $T(I)$, neglect the effluent group and go to test of the next parameter. If all design parameters have been tested, ignore outfall group and go to Task 3, Activity 1.
- If Impact (I) is greater than $T(I)$, include effluent group in segmentation, let $N = N + 1$ denote the index number corresponding to the segment with this effluent group at its upstream end, and go to Task 3, Activity 6.

TASK 3, ACTIVITY 6—COMPUTE FLOW RATE AND CONCENTRATIONS FOR THE EFFLUENT GROUP

Objective

Compute the total flow rate $[Q_g(N)]$ and concentration $[C_g(I, N)]$ of each pertinent parameter for the effluent group.

Outputs

- $Q_g(N)$ in l/sec
- $C_g(I, N)$ in mg/l.

Inputs

- Task 2, Activity 2—Tributary flow rates
- Task 2, Activity 3—Effluent flow rates
- Task 2, Activity 5—Effluent concentrations
- Task 2, Activity 6—Tributary concentrations.

Procedure

- Compute the sum of effluent flows from all effluents in group N:

$$Q_g(N) = \sum_s Q_s$$

- Compute the summed concentrations for each effluent parameter (I).

$$C_g(I, N) = \frac{\sum_s C_s(I) * Q_s}{Q_g}$$

- Enter flow rate $Q_g(N)$, and parameter concentrations $C_g(I, N)$ in appropriate Computation Table, (E.g., Tables G-8, G-9).
- Go to Activity 7.

TASK 3, ACTIVITY 7—SPECIFY RIVER MILE OF GROUPED DISCHARGE POINT

Objective

Assign a point river mileage to the location of effluent group N, segment N.

Output

- Location in river miles of discharge group point.

Inputs

- Task 1 Activity 4—Situation Map.

Procedure

- Find the arithmetic mean of the river miles of the group using the expression

$$R.M._{mean} = \frac{1}{n} \sum_{L=1}^{n} R.M._L$$

where n = number of outfalls in the group.

$R.M._L$ = river mile of Lth outfall as given in Situation Map

$R.M._{mean}$ = the upper end of segment N and is also the grouped effluent source location.

- Enter $R.M._{mean}$ into the Computation Tables (i.e., Tables G-8, G-9) as both the end of the previous, upstream segment N-1, and the beginning of the new segment N.
- Go to Activity 8.

TASK 3, ACTIVITY 8—DETERMINE STREAM CHARACTERISTICS

Objective

Determine the average values of stream depth [H(N-1)], flow velocity [U(N-1)], stream flow [Q(N-1)] and water temperature [Temp (N-1)] over the system duration for segment N-1.

Outputs

- Stream Depth—H(N-1) in feet
- Flow Velocity—U(N-1) in ft/sec
- Stream Flow—Q(N-1) in liters/sec
- Water Temperature—Temp (N-1) in °C.

Inputs

- Task 2, Activity 1—Stream Flow Data
- Task 3, Activity 7—Segment Bounds

Discussion

The physical characterization is now performed on segment N-1 because the identification of discharge group N defines the downstream end point of segment N-1. This characterization is to be made using available Geological Survey data. In general the resolution of this data is larger than the segment size. Therefore, one physical characterization per segment is usually made. However, if stream data with finer resolution is available, the physical variables may be given for a much finer resolution.

Procedure

- Identify the nearest Geological Survey stations from segment N-1.
- Specify the segment stream parameters (average flow velocity (U), depth (H), stream flow (Q), and temperature) by
  1) linearly interpolating the data over the system duration from the stations identified above
  2) averaging this data over the system duration.
- Enter output in Computation Tables, (Tables G-8, G-9) on row N-1.
- Go to Activity 9.

TASK 3, ACTIVITY 9—COMPUTE SEGMENT DECAY COEFFICIENT

Objective

Find the decay coefficients $[k_d(I,\ N-1)]$ for each design parameter in segment N-1.

Output

- Parameter Decay Coefficients $k_d(I,\ N-1)$ in days

Inputs

- Task 1, Activity 2—Effluent Types
- Task 2, Activity 1—Stream Data

- Task 3, Activity 2—Guidelines
- Task 3, Activity 8—Stream Characterization

Procedure

For each design parameter perform the following steps:

- Find the parameter decay coefficient for each outfall $k_d(I, S)$ of the group according to its type (I) and the guidelines presented in Task 3, Activity 2.
- Compute the combined decay coefficients for each parameter (I):

$$k_d(I, N-1) = \frac{\sum_S C_S I * Q_S * k_d(I, S)}{\sum_S C_S(I) * Q_S}$$

- Enter $k_d(I, N-1)$ in the appropriate Computation Table (Table G-8 or G-9 on row N.
- Go to Activity 10.

TASK 3, ACTIVITY 10—FIND SEGMENT REAERATION COEFFICIENT

(Note: Skip this activity if DO is not of design interest.)

Objective

Find the reaeration coefficient $k_a(N-1)$ for segment N-1.

Output

- Reaeration coefficient $k_a(N-1)$ in day^{-1}.

Inputs

- Task 3, Activity 8—Stream Depths
- Figure G-11.

Procedure

- Enter Figure G-11 on the absissa at the segment (N-1) depth value.
- Trace vertically upwards to the line corresponding to the segment (N-1) stream velocity.
- Trace horizontally to ordinate position corresponding to the segment (N-1) value of k_a.

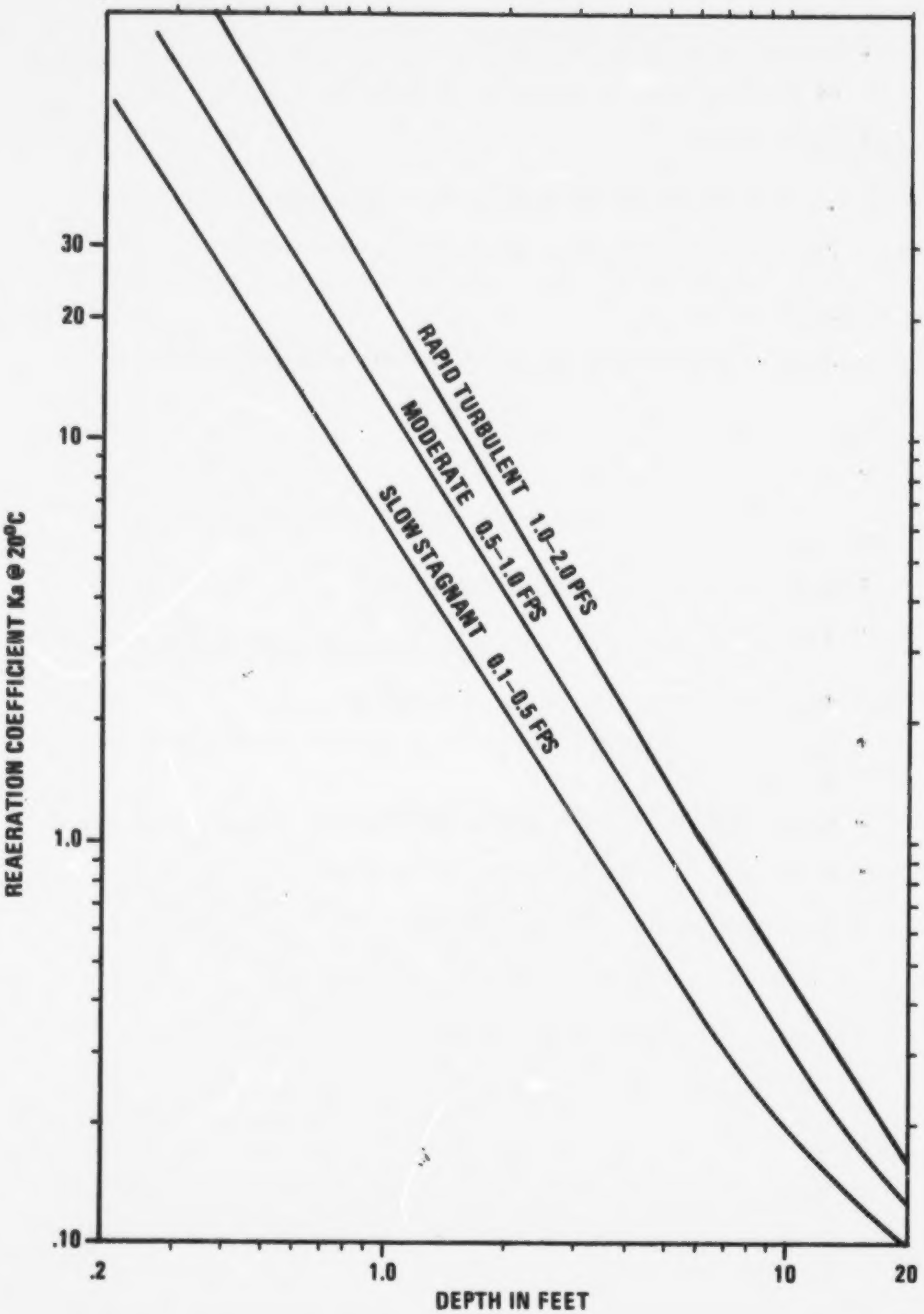


Figure G-11. Reaeration Coefficient (k_a) as a Function of Depth

- Enter k_a(N-1) on the Computation Table, Table G-9 on segment Row (N-1).
- Go to Activity 11.

TASK 3, ACTIVITY 11—FIND THE DO SATURATION LEVEL

(Note: Skip this activity if DO is not of design interest.)

Objective

Find the DO saturation level, C_{sat}(N-1) for segment N-1.

Output

- DO Saturation Level C_{sat}(N-1) in mg/L

Inputs

- Task 3 Activity 8—Stream Temperature
- Task 2 Activity 5—Figure G-7.

Procedure

- Using the stream temperature for segment N-1 and Figure G-7 find C_{sat} directly.
- Enter C_{sat} in Computational Table, Table G-9, on segment row N-1.
- If NN=1, go to Task 4; If NN=0, go to Activity 1.

TASK 4

CHARACTERIZE SEGMENTS

The procedure for computation of a stream parameter profile is dependent on the behavior of that design parameter. The three basic physical systems which will be dealt with here are non-conservative coupled, non-conservative uncoupled and conservative uncoupled. The first category, descriptive of complex systems such as the BOD-DO system, is dealt with in Task 4A. The latter two parameter types are handled in Tasks 4B and 4C, respectively.

The solution of parameter profiles in each of these sections consists of a number of activities which should be performed in the sequence shown in the flow chart in Figure G-12. For each design parameter the activities are performed iteratively for each segment, beginning with the headwaters and continuing to the river mouth.

The computed values to be evaluated in Task 4 should be tabulated in a computation table for ease in later use. Table G-10 illustrates a format for the BOD-DO case to contain values found in Tasks 4 and 5.

TASK 4, CONTROLS: SELECT PARAMETER PROFILE COMPUTATION

Objective

Select a pertinent design parameter and choose the proper profile computation.

Output

- Specification of a design parameter and which subtask of Task 4 to use.

Inputs

- Task 1, Activity 2 — Field Data
- Task 1, Activity 6 — Design Parameters

Procedure

- Select Design Parameter.
- Initialize segment sequence index by letting N = 1.
- If the design parameter is dissolved oxygen, go to Task 4A.
- If the design parameter is non-conservative uncoupled go to Task 4B.
- If the design parameter is conservative uncoupled, go to Task 4C.

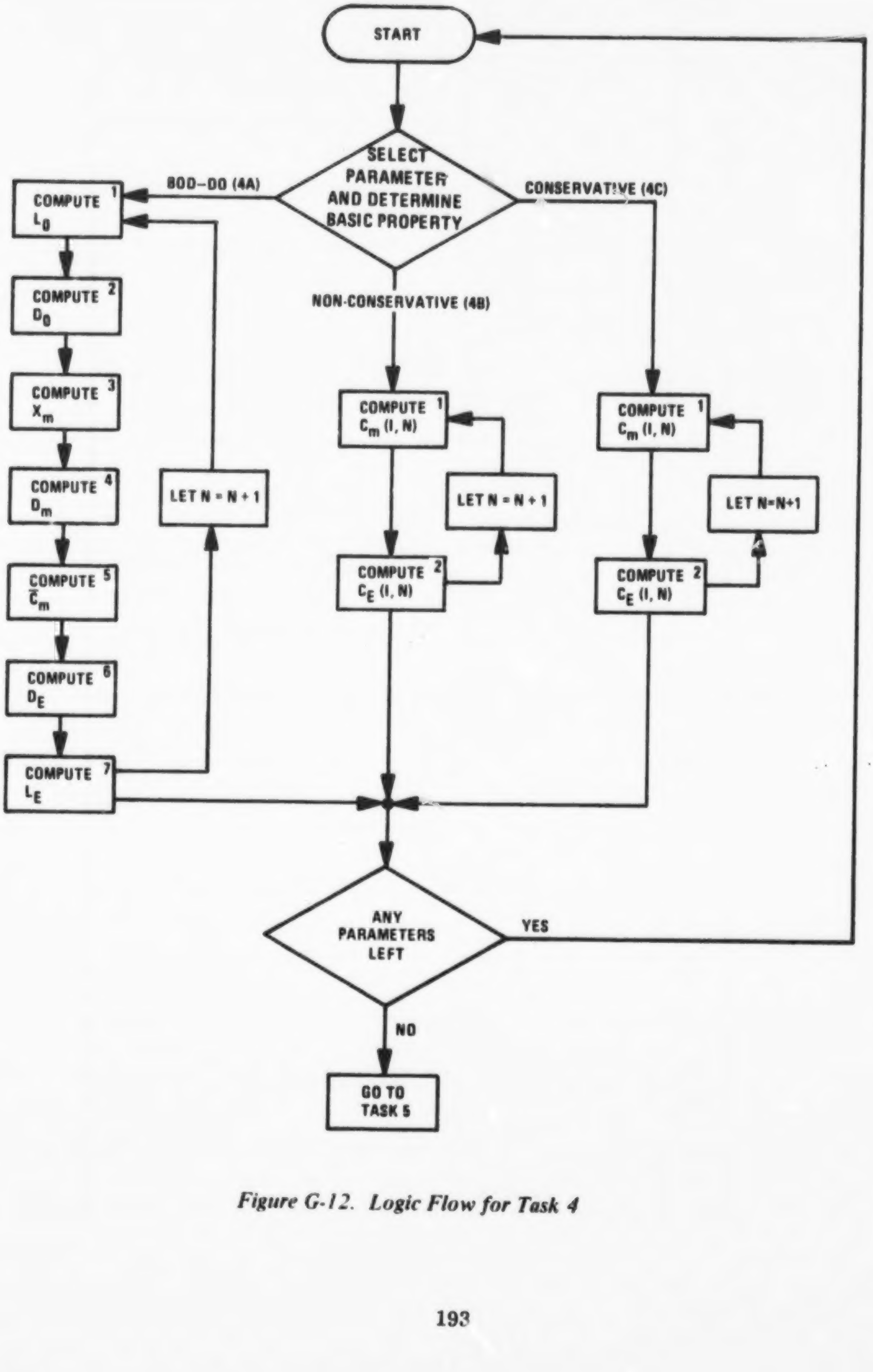


Figure G-12. Logic Flow for Task 4

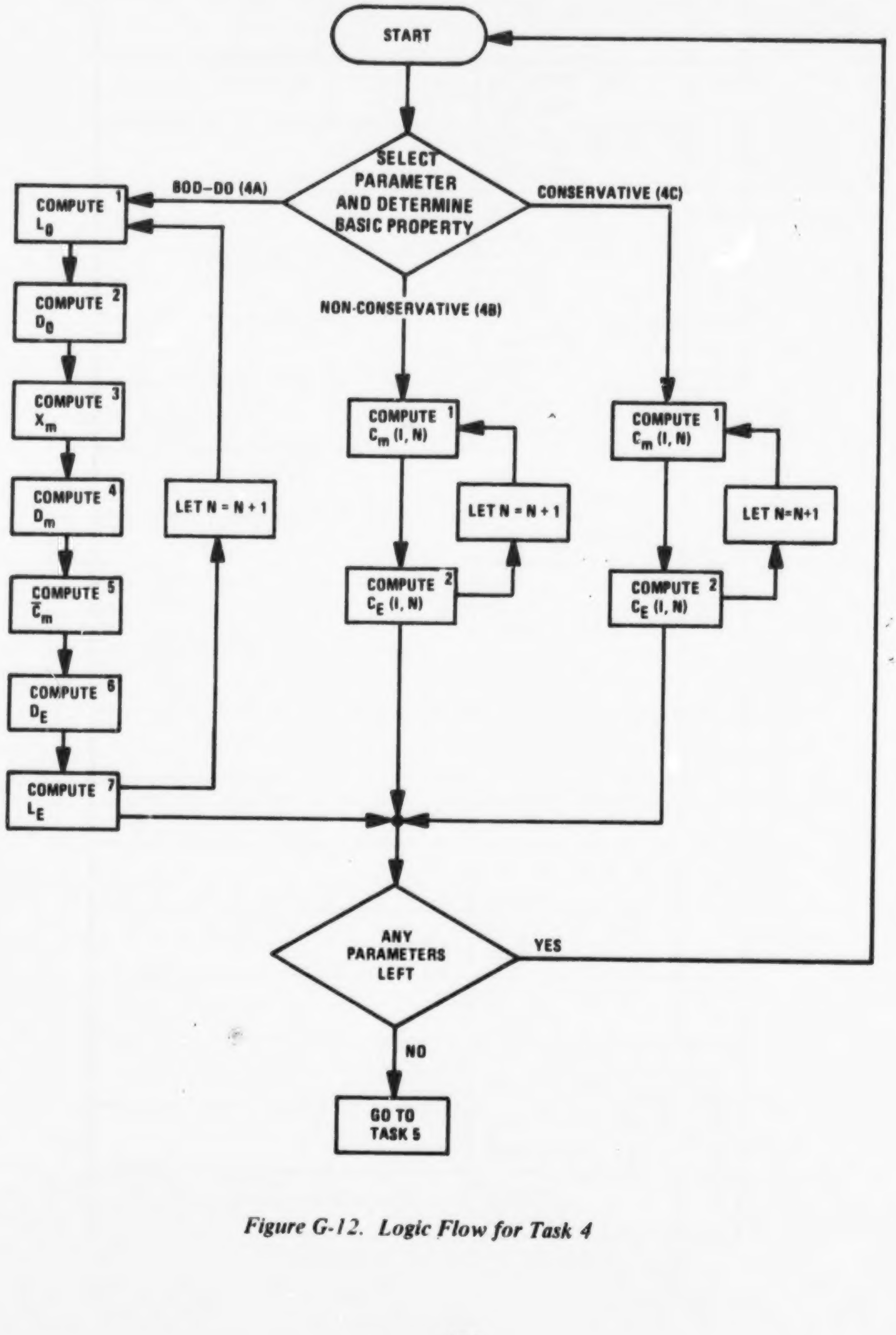


Figure G-12. Logic Flow for Task 4

Table G-10. Computation Table No. 2 for BOD-DO

N	Segment Position (RMI)		x_E	L_0	D_0	x_m	D_m	C_m	D_{bk}	D_E	L_E	σ	C_t	P	R	D_1^*	C_1^*	P_1^*
Segment Number	Upstream End	Downstream End	Segment Length (miles)	Initial BOD Conc. (mg/l)	Initial DO Deficit (mg/l)	Max Conc. Distance (miles)	Max DO Deficit (mg/l)	Max DO Conc. (mg/l)	Background DO Def.	Segment End DO Def. (mg/l)	Segment End BOD Conc. (mg/l)	DO Stand. Deviation (mg/l)	DO Conc. Threshold (mg/l)	Initial Priority Rating	Inter-Seg Correlation	Adjusted DO Def. (mg/l)	Adjusted DO Conc. (mg/l)	Ultimate Prior. Rating #1
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		

TASK 4A, ACTIVITY 1 — COMPUTE $L_0(N)$

Objective

Compute BOD concentration at upstream end of the N^{th} segment $[L_0(N)]$.

Output

- $L_0(N)$ in mg/1.

Inputs

- Computation Table G-8—$Q_g(N)$, $L_g(N)$
- Computation Table G-10 - $L_E(N-1)$

Procedure

- For the segment under consideration (Segment "N"), compute:

$$L_0(N) = \frac{Q_g(N) L_g(N) + Q(N-1)\ L_E(N-1)}{Q(N-1) + Q_g(N)}$$

Except: for N=1, assume $L_E(N-1) = 0$

- Enter $L_0(N)$ on Computation Table G-10.
- Go to Activity 2.

TASK 4A, ACTIVITY 2 — COMPUTE $D_0(N)$

Objective

Compute initial DO deficit at upstream end of the N^{th} segment $[D_0(N)]$.

Output

- $D_0(N)$ in mg/1.

Inputs

- Computation Table G-8 — $Q_g(N)$, $D_g(N)$, $Q(N-1)$, $C_{sat}(N)$
- Computation Table G-10 - $D_E(N-1)$

Discussion

If the saturation DO concentration is different in segments N-1 and N, the DO deficit at the end of the upstream segment must be compensated for. (Note: step 1 of procedure).

Procedure

- For the segment under consideration (Segment "N") compute:

$$D'_E(N-1) = D_E(N-1) + [C_{sat}(N) - C_{sat}(N-1)]$$

if $D'_E(N-1) < 0$, let $D'_E(N-1) = 0$

- Compute

$$D_0(N) = \frac{Q_g(N)*D_g(N) + Q(N-1)*D'_E(N-1)}{Q(N-1) + Q_g(N)}$$

if N=1 assume $D'_E(N-1) = 0$

- Enter $D_0(N)$ on Computation Table G-10.

- Go to Activity 3.

TASK 4A, ACTIVITY 3 — DETERMINE $x_m(N)$

Objective

Compute the location of maximum expected DO deficit in the N^th segment $[x_m(N)]$.

Output

- $x_m(N)$ in miles.

Inputs

- Computation Table G-8 — $U(N), k_d(N), k_d(N)$.

- Computation Table G—10 — $L_0(N)$, $D_0(N)$, $x_E(N)$.

Procedure

There are two alternate procedures for this activity. The first uses direct computation of the values through use of equations. The second replaces direct computation with a nomograph.

Alternative 1

- For the segment of interest (segment N) compute

$$Z_1 = \frac{D_0(N)* \ k_a(N) - k_d(N)}{L_0(N)*k_d(N)}$$

- Compute $Z_2 = \frac{k_a(N)}{k_d(N)} (1-Z_1)$

- Find $Z_3 = \ln(Z_2)$ using a table of natural logrithms.

- Compute $x_c(N) = \frac{U(N)* [16.36] *Z_3}{k_a(N) - k_d(N)}$

- Compare $x_c(N)$ with $x_E(N)$.

  If $x_c(N)$ is greater than $x_E(N)$, set $x_m(N) = x_E(N)$.

  If $x_c(N)$ is less than $x_E(N)$, set $x_m(N) = x_c(N)$.

  Enter $x_m(N)$ on Computational Table G-10.

- Go to Activity 4.

Alternative 2

Note: the condition for use of the nomograph method is that k_a must be less than 10.

- Refer to Figure G-13 through G-15. Figure G-16 is provided as a key to these figures.

- Enter Figure G-13 on the abscissa with $D_0(N)$. Trace vertically to the isopleth corresponding to $L_0(N)$. Trace horizontally to read $D_0(N)/L_0(N)$.

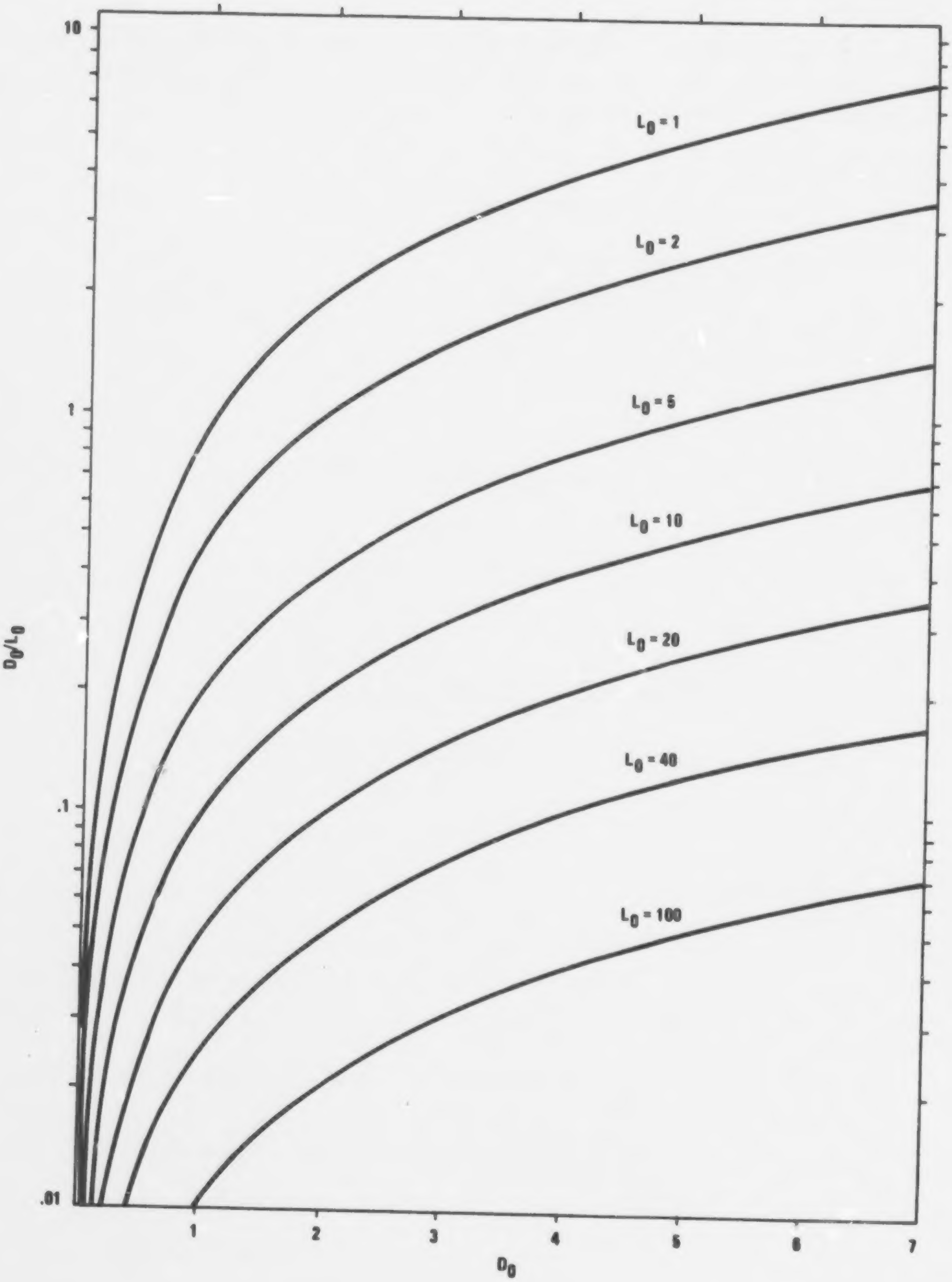


Figure G-13. DO Nomograph—Part 1

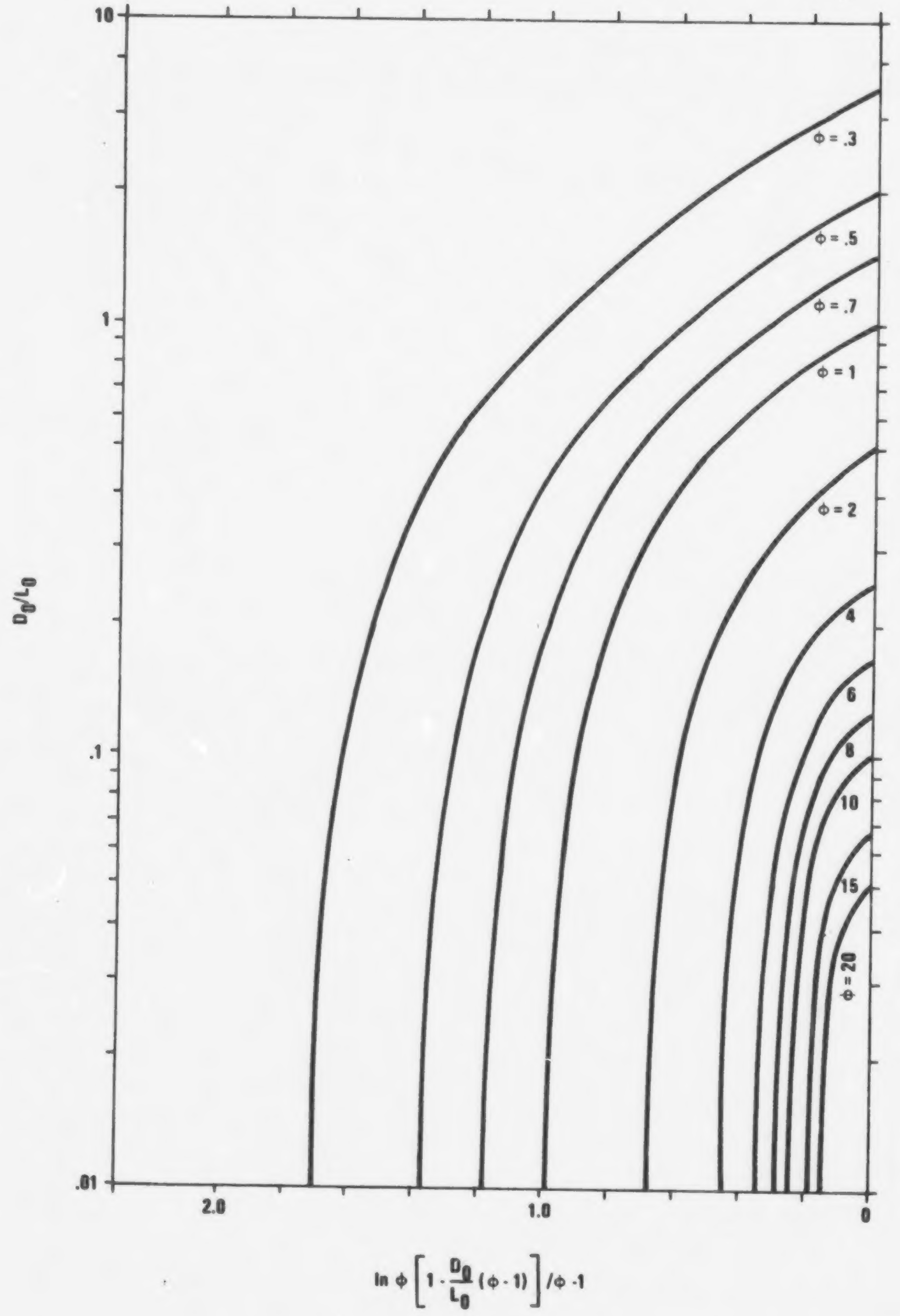


Figure G-14. DO Nomograph—Part 2

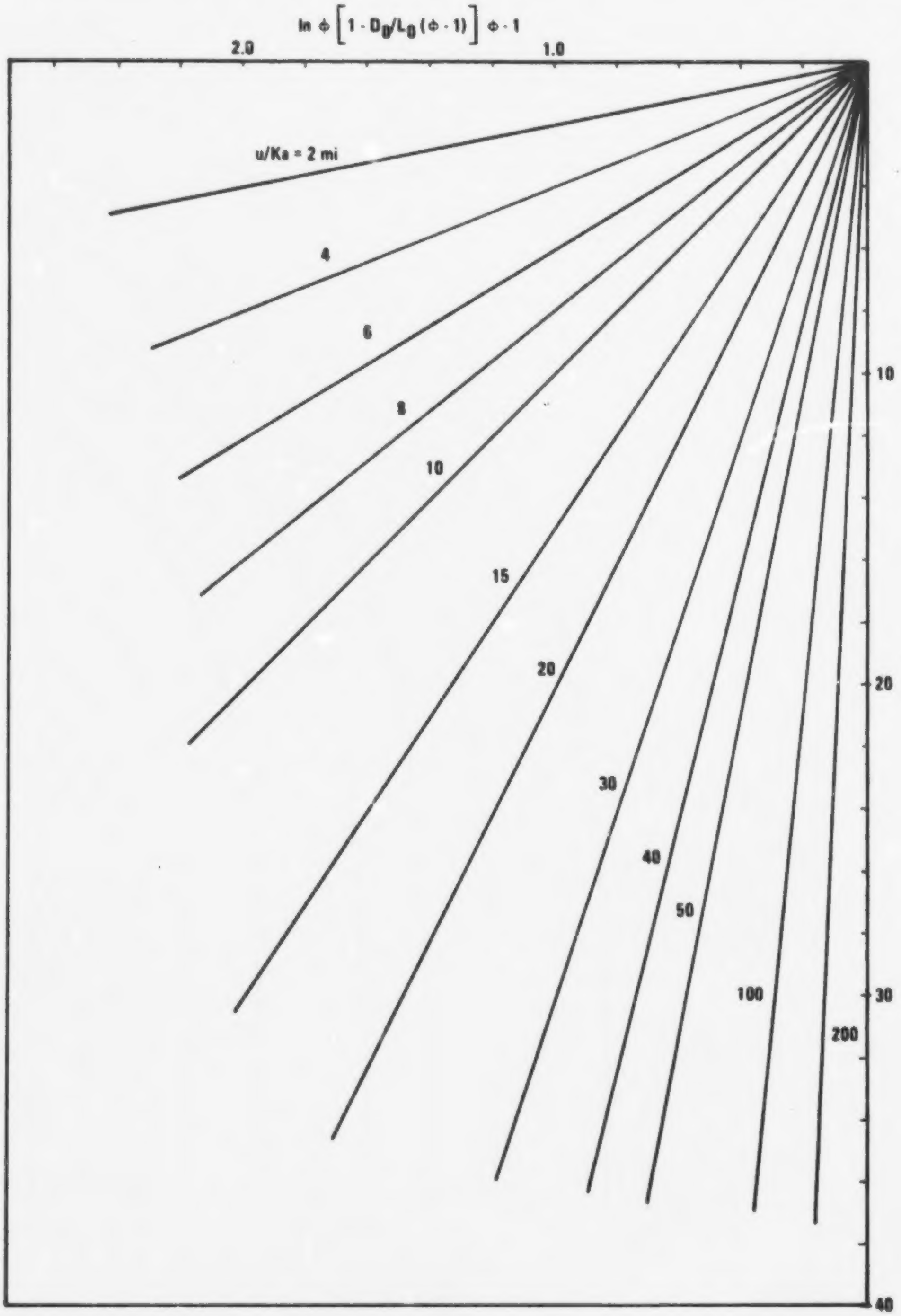


Figure G-15. DO Nomograph–Part 3

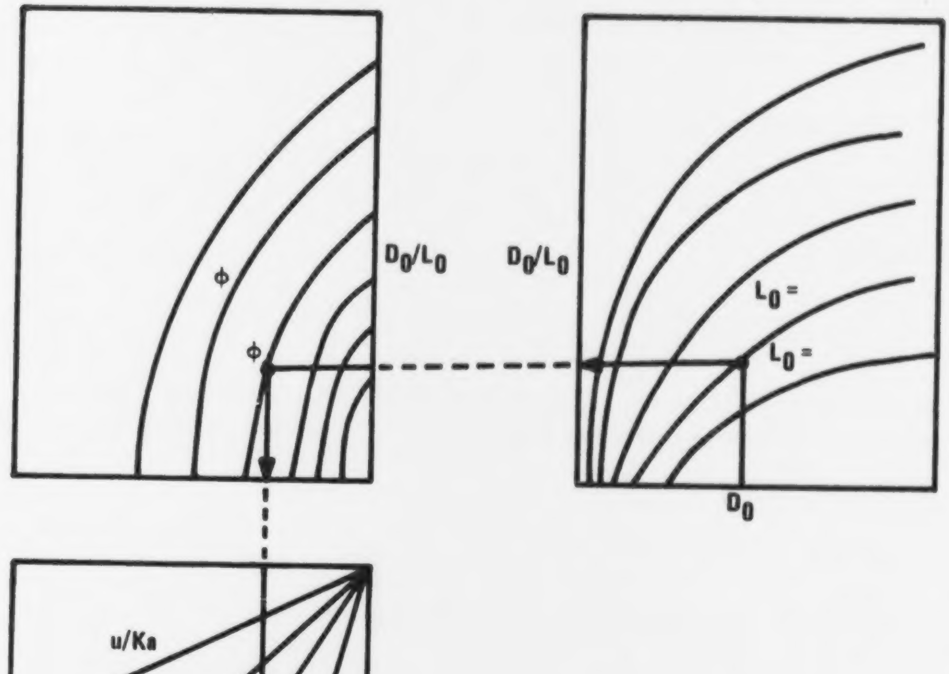


Figure G-16. Nomograph Key

- Compute

  $\phi(N) = k_a(N)/k_d(N)$

- Enter Figure G-14 on the ordinate with D_0/L_0. Trace horizontally to the isopleth corresponding to $\phi(N)$. Trace vertically downward to abscissa to read

$$A\,(N) = \frac{\ln \phi \left[1 - \frac{D_0}{L_0}(\phi - 1)\right]}{\phi - 1}$$

- Compute

$$U/k_a = \frac{U(N)^{*}\,[16.36]}{k_a(N)}$$

- Enter Figure G-15 on the abscissa with A (N). Trace vertically downward to the isopleth corresponding to U/k_a. Trace horizontally to read $x_c(N)$ on the ordinate.

- Compare $x_c(N)$ with $x_e(N)$

  If $x_c(N)$ is greater than $x_E(N)$, set $x_m(N)=x_E(N)$

  If $x_c(N)$ is less than $x_E(N)$, set $x_m(N)=x_c(N)$

- Enter $x_m(N)$ on Computational Table G-10.

- Go to Activity 4).

TASK 4A, ACTIVITY 4 — COMPUTE $D_m(N)$

Objective

Compute the magnitude of the maximum expected DO deficit for the N^{th} segment $[D_m(N)]$.

Output

- $D_m(N)$ in mg/1.

Inputs

- Computation Table G-8 — $U(N)$, $k_d(N)$, $k_a(N)$.
- Computation Table G-10 $L_0(N)$, $D_0(N)$, $x_m(N)$.

Discussion

To compute D_m, we must evaluate the equation:

$$D_m = \frac{k_d L_0}{k_a - k_d} \left(e^{-k_d x_m / U} - e^{-k_a x_m / U} \right) + D_0 e^{-k_a x_m / U}$$

The following procedure is a step-by-step order of computation.

Procedure

- Compute $A_1(N) = \frac{k_a(N) \; x_m(N)}{U(N) \; (16.36)}$
- Compute $B_1(N) = e^{-A_1(N)}$ using exponential tables in a math handbook.
- Compute $A_2(N) = \frac{k_d(N) \; x_m(N)}{U(N) * (16.36)}$
- Compute $B_2(N) = e^{-A_2(N)}$ using exponential tables
- Compute

$$D_m(N) = \frac{k_d(N) L_0(N)}{k_a(N) - k_d(N)} \left(B_2(N) - B_1(N) \right) + D_0(N) * B_1(N)$$

- Enter $D_m(N)$ on Computation Table G-10.

- Go to Activity 5.

TASK 4A, ACTIVITY 5 — DETERMINE $C_m(N)$

Objective

Compute the minimum expected oxygen concentration for the N^{th} segment $[C_m(N)]$.

Output

- $C_m(N)$ in mg/l.

Inputs

- Task 2, Activity 4 — D_{bk}.

- Computation Table G-8 — $C_{sat}(N)$.

- Computation Table G-10 — $D_m(N)$.

Procedure

- Compute for segment N

$$C_m(N) = C_{sat}(DO,N) - D_m(N) - D_{bk}(DO,N).$$

- Enter $C_m(N)$ and $D_{bk}(N)$ on Computation Table G-10.

- Go to Activity 6.

TASK 4A, ACTIVITY 6 — COMPUTE $D_E(N)$.

Objective

Compute the DO deficit at the end of the N^{th} segment $[D_E(N)]$.

Output

- $D_E(N)$, DO deficit at end of segment in mg/l.

Inputs

- Computation Table G-8 — $U(N)$, $k_d(N)$, $k_a(N)$.
- Computation Table G-10 — $L_0(N)$, $D_0(N)$, $x_E(N)$.

Procedure

- If $x_m(N) = x_E(N)$, then set $D_E(N)=D_m(N)$ and go to Step 7. Otherwise, proceed to Step 2.
- Compute

$$A'_1(N) = \frac{k_a(N)x_F(N)}{U(N) * (16.36)}$$

- Compute

$$B'_1(N) = \exp\left[-A'_1(N)\right]$$

- Compute

$$A'_2(N) = \frac{k_d(N)x_E(N)}{U(N) * (16.36)}$$

- Compute

$$B'_2(N) = \exp\left[-A'_2(N)\right]$$

- Save the value of $B'_2(N)$ for the next Activity.
- Compute

$$D_E(N) = \frac{k_d(N)L_0(N)}{k_a(N) - k_d(N)} \left[B'_2(N) - B'_1(N)\right] + D_0(N)*B'_1(N).$$

- Enter $D_E(N)$ on Computation Table G-10.
- Go to Activity I.

TASK 4A, ACTIVITY 7 — COMPUTE L_E

Objective

Compute the BOD load at the downstream end of the N^{th} segment $[L_E(N)]$.

Output

- $L_E(N)$ in mg/l.

Inputs

- Computation Table G-8 — $U(N)$, $k_a(N)$.
- Computation Table G-10 — $L_0(N)$, $x_E(N)$.
- Task 4A, Activity 6 — $B'_2(N)$.

Discussion

To compute L_E, we must evaluate the equation

$$L_E(N) = L_0(N) \exp\left[-k_d(N)\, x_E(N) / U(N)\right] = L_0(N)*B'_2(N)$$

Procedure

- Compute $L_E(N) = L_0(N)*B'_2(N)$.
- Enter $L_E(N)$ in Computational Table G-10.
- If end of last segment reached, go to Task 4, start, if not, increment N by one and go to Task 4A, Activity 1.

TASK 4B, ACTIVITY 1 — COMPUTE C_m (I, N) FOR EACH SEGMENT

Objective

Compute the maximum concentration of the non-conservative parameter in the N^{th} segment $[C_m(I, N)]$.

Output

- $C_m(I, N)$ in units appropriate to standards.

Inputs

- Task 2, Activity 4 — $C_{bk}(I)$

- Computation Table G-9 — $Q_g(N)$, $Q(N-1)$, $C_g(N)$.
- Computation Table G-10 — $C_E(N-1)$

Discussion

The maximum concentration of a non-conservative parameter occurs at the effluent group point of discharge (i.e., $x_m(I, N) = 0$).

Procedure

- Compute using data from Table 3

$$C_0(I, M) = \frac{C_E(I, N-1)*Q(N-1) + C_g(N)*Q_g(N)}{Q(N-1) + Q_g(N)}$$

  at the most upstream discharge of any tributary assume $C_E(I, N-1) = 0$.

- Add the background parameter concentration $C_{bk}(I, N)$.

$$C_m(I, N) = C_0(I, N) + C_{bk}(I, N)$$

- Enter $C_m(I, N)$ and $C_{bk}(I, N)$ in the computational table (e.g. Table G-10).
- Go to Activity 2.

TASK 4B, ACTIVITY 2 — COMPUTE $C_E(I, N)$ FOR EACH SEGMENT

Objective

Compute the concentration of non-conservative parameter at the end of the N^{th} segment [$(C_E(I, N)$].

Output

- $C_E(I, N)$

Inputs

- Computation Table G-9 - $U(N)$, $k_d(I, N)$.
- Computation Table G-10 - $C_m(I, N)$, $x_E(N)$.

Procedure

- Compute $A'_2(I, N) = \dfrac{k_d(I, N)*x_E(N)}{U(N)}$
- Compute

$$C'_E(I, N) = C_0(I, N)*e^{-A'_2(I, N)}$$

- Allowing the probability that

  $Q(N) \neq Q(N-1) + Q_g$

  due to small flow additions within segment N,

$$C_E(I, N) = \frac{C'_E(I, N)*[Q(N-1) + Q_g(N)]}{Q(N)}$$

- Enter $C_E(I, N)$ in computation table (e.g., Table G-10)
- If C_E has been computed for all parameters, go to Task 5; if not, go to Task 4 Start.

TASK 4C, ACTIVITY 1 — COMPUTE C_m FOR EACH SEGMENT

Objective

Compute the maximum concentration of the conservative parameter in the N^{th} segment $[C_m(I, N)]$.

Output

- $C_m(I. N)$ in units appropriate to standards.

Inputs

- Task 2, Activity 4 — $C_{bk}(I)$
- Computation Table G-9 — $Q_g(N)$, $Q(N-1)$, $C_g(N)$.
- Computation Table G-10 — $C_E(I, N-1)$

Procedure

- Compute using data from Table 3

$$C_o(I,N) = \frac{C_E(I,N-1)*Q(N-1) + C_g(N)*Q_g(N)}{Q(N-1) + Q_g(N)}.$$

at the most upstream discharge of any tributary assume $C_E(I,N) = 0$.

- Add the background parameter concentration, $C_{bk}(I,N)$

$$C_m(I,N) = C_0(I,N) + C_{bk}(I,N)$$

- Enter $C_m(I,N)$ and $C_{bk}(I)$ on the computational table (e.g., Table G-10).
- Go to Activity 2.

TASK 4C, ACTIVITY 2 — COMPUTE $C_E(I,N)$ FOR EACH SEGMENT

Objective

Compute the concentration of conservative parameter at the end of the N^th^ segment $C_E(I,N)$.

Output

- $C_E(I,N)$.

Inputs

- Computation Table G-9 — Q(N), Q(N-1), $Q_g(N)$.
- Task 4C, Activity 1 — $C_0(I,N)$.

Procedure

- Allowing the probability that

  $Q(N) \neq Q(N-1) + Q_g$

  due to small flow additions within segment N,

$$C_E(I,N) = \frac{C_0(I,N)*\left[Q(N-1) + Q_g(N)\right]}{Q(N)}.$$

- Enter $C_E(I, N)$ in computational table (e.g., Table G-10).
- If C_E has been computed for all parameters, go to Task 5; if not, go to Task 4, Start.

TASK 5

DETERMINATION OF SEGMENT PRIORITY RATINGS

The ultimate priority ratings of a segment (N) are functions of the maximum parameter degradations, standard deviations, and inter-segment correlations for each parameter (I). In this task these factors are found and combined in the direct computation of the ultimate priority ratings. The logical flow of this task is given below in Figure G-17.

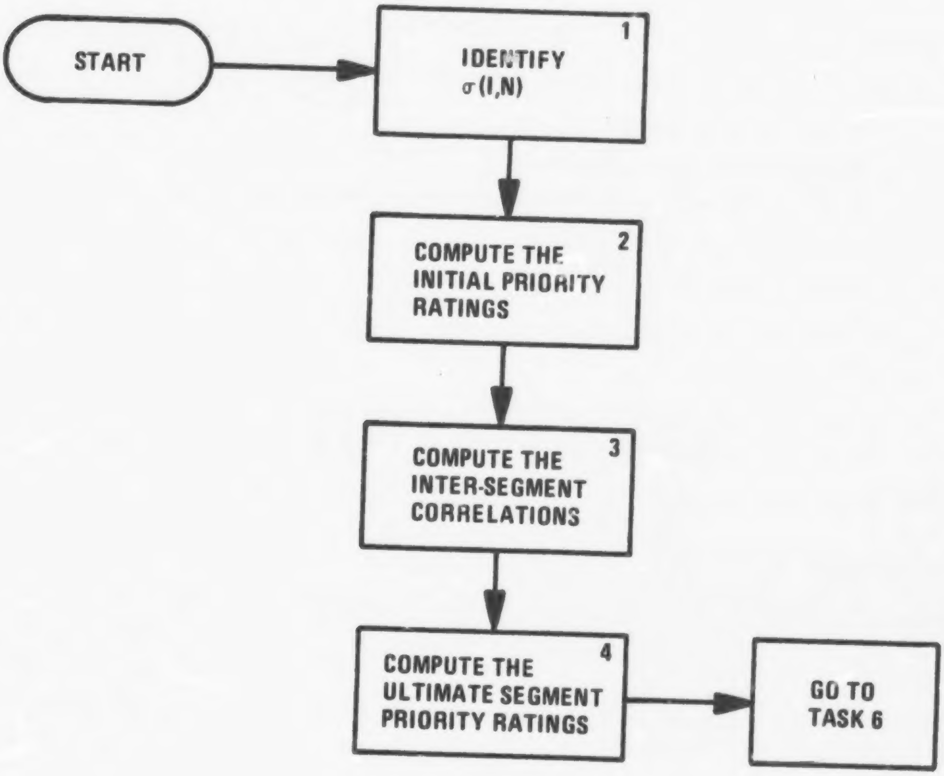

START
IDENTIFY
σ (I,N)
1
COMPUTE THE INITIAL PRIORITY RATINGS
2
COMPUTE THE INTER-SEGMENT CORRELATIONS
3
COMPUTE THE ULTIMATE SEGMENT PRIORITY RATINGS
4
GO TO TASK 6

Figure G-17. Logic Flow for Task 5

TASK 5, ACTIVITY 1— IDENTIFY $\sigma(I,N)$

Objective

For each design parameter (I) and segment (N) find the parameter standard deviation $[\sigma(I,N)]$.

Output

- $\sigma(I,N)$.

Input

- Task 1, Activity 2—STORET Data.

Procedure

- Obtain a STORET Statistical Summary Retrieval:

  1) for all stations of the basin subset
  2) for the design parameters
  3) retrieval by fixed date interval over the system duration.

  NOTE: It is best to retrieve ovef the system duration (a particular season), but for several different years.

  The parameter standard deviations for each parameter are printed on this retrieval.

- Locate the nearest STORET station to segment N which has at least 2 parameter measurements, over the system duration, of parameter (I).
- Enter this station's $\sigma(I,N)$ in Computational Table G-10.
- Go to Activity 2.

TASK 5, ACTIVITY 2— COMPUTE INITIAL PRIORITY RATING

Objective

For each design parameter (I) and segment (N) compute the Initial Priority Rating P (I, N).

Output

- P (I,N).

Inputs

- Task 1, Activity 1— Standards Thresholds
- Computation Table G-10 - C_m (I, N), σ(I, N).

Procedure

- Find the difference between expected concentration and the threshold concentration:
  1) For the case of dissolved oxygen, compute

     $G(I,N) = C_T(I,N) - C_m(I,N)$.

     NOTE: When this value increases, the degradation of the stream increases.
  2) In the not to exceed the threshold parameters, compute

     $G(I,N) = C_m(I,N) - C_T(I,N)$

     NOTE: Again the value increases with increasing degradation.
- Compute $P(I,N) = \dfrac{G(I,N)}{\sigma(I,N)}$
- Enter P(I, N) in Computation Table G-10.
- Go to Activity 3.

TASK 5, ACTIVITY 3— COMPUTE INTER-SEGMENT CORRELATIONS

Objective

For each design parameter (I) and segment (N) compute the effect of immediate upstream segment, as measured by the Inter-Segment Correlation R(I, N).

Output

- R(I, N) dimensionless.

Inputs

- Task 2, Activity 4— C_{bk} (I)
- Computation Table G-8— k_d(I, N), k_a(I, N), U(N), Q(N), Q_g(N).

- Computation Table G-10— $L_E(N-1)$, $D_E(N-1)$, $x_m(N)$, $D_m(N)$, $C_E(I,N)$, $C_m(I,N)$.

Procedure

- For the coupled BOD-DO case:
  1) Take $L_E(N-1)$ and $D_E(N-1)$ and compute their dilution due to the effluent source in segment N, using the equations:

$$L'_E(N-1) = \frac{L_E(N-1) * Q(N-1)}{Q(N-1) + Q_g(N)}$$

$Q(N-1)$ = stream flow in segment N-1

$Q_g(N)$ = effluent group flow in segment N.

$$D'_E(N-1) = \frac{D'_E(N-1) \; * \; Q(N-1)}{Q(N-1) + Q_g(N)}$$

  2) Compute the deficit at $x_m(N)$ due only to $L'_E(N-1)$ and $D'_E(N-1)$ using the equations,

$$D_{x_m}(N) = \left[\frac{L'_E(n-1)\, k_d(N)}{k_a(N) - k_d(N)}\right] \cdot \left\{\exp\left[-k_d(N) \cdot x_m(N)/U(N)\right] - \exp\left[-k_a(N) \cdot x_m(N)/U(N)\right]\right\} + D'_E(N-1) \cdot \exp\left[-k_a(N) \cdot x_m(N)/U(N)\right]$$

  3) Compute R(N) as

$$R(DO, N) = \frac{D_{x_m}(N)}{D_m(N)}$$

- For all uncoupled parameters simply compute

$$R(I, N) = \frac{C_E(I, N-1)}{C_m(I, N) - C_{bk}(I)} .$$

- Enter R(I, N) in Computational Table G-10.
- Go to Activity 4.

TASK 5, ACTIVITY 4— COMPUTE ULTIMATE SEGMENT PRIORITY RATINGS

Objective

Compute the ultimate segment priority ratings $[P_n^*(I, N)]$ for a phased implementation of sampling stations, as a function of the probability of violation and the information available from segments already being monitored.

Output

- Ultimate segment priorities, $P_n^*(I, N)$.

Inputs

- Computation Table G-10— $R(I, N)$, $C_m(I, N)$, $D_m(N)$, $C_T(N)$

Discussion

The priority of each segment must be re-computed as phased implementation of a surveillance system takes place, or is imagined to take place.

The uncoupled case will be presented first, then a modification of the procedure will be identified for the coupled BOD-DO case.

Procedure

- Based on the implementation (selection) of segment q as a sampling station, perform the following:
    a) Compute the cross-correlations $R(I, N, q)$ between segment q and segments N, for all segments $N \neq q$ whose waters eventually flow in segment q, or vice versa, using:

$$R(I, N, q) = \begin{array}{ll} R(I, N) \cdot R(I, N+1) \cdot \ldots\ldots \cdot R(I, q-1) & \text{if } N < q \\ R(I, q) \cdot R(I, q-1) \cdot \ldots\ldots\ldots \cdot R(I, N-1) & \text{if } N > q \\ 1 \quad \text{if} \quad N = q. & \end{array}$$

If the waters from segment q never flow with segment N, or vice versa, then $R(I, N, q) = 0$.

b) Compute
$$C_1^*(I, N) = C_m(I, N)\left[1-R(I, N, q)\right].$$

c) Compute the ultimate priority ratings for all segments N:

$$P_1^*(I, N) = \frac{C_1(I, N) - C_t(I, N)}{\sigma(I, N)}$$

where the subscript on Panel C* and ρ^* denotes the number of stations already implemented (selected).

- Based on the selection of segment r as the second stations to be implemented, perform the following:

  a) Compute the cross-correlations $R(I, N, r)$ between segment r and all other segments, using the above definition of $R(I, N, g)$.

  b) Compute:

  $$C_2^*(I, N) = C_1^*, \ (I, N)\ [1-R(I, N, r)]\ .$$

  c) Compute:

  $$P_2^*\ (I, N) = \frac{C_2^*\ (I, N) - C_t(I, N)}{\sigma\ (I, N)}\ .$$

- Assuming the nth implementation takes place on segment s, for all segments N which have not yet been selected for monitoring, perform the following computations for all values of n of interest:

  a) Compute:
  $$C_n^*(I, N) = C_{n-1}^*(I, N)\left[1-R(I, N, s)\right]$$

  b) Compute:
  $$\alpha_n^*(I, N) = \frac{C_n^*(I, N) - C_t(I, N)}{\sigma\ (I, N)}\ .$$

- For the BOD-DO case, for the nth implementation in segment s, n = 1, 2 . . . . for all segments N which have not yet been selected for monitoring, perform the following:

  a) Compute:
  $$R(I, Ns)$$

  b) Compute:
  $$D_n^*(N) = D_{n-1}^*\ [1-R(I, N, s)]$$

$$C_n^*(DO,N) = \frac{C_T(DO,N) - C_n(DO,N)}{(DO,N)}.$$

c) Compute:

$$P_n^*(DO,N) = \frac{C_T(DO,N) - C_n^*(DO,N)}{(DO,N)}.$$

- Enter $P^*_n(I,N)$ in Computation Table G-10.
- Go to Task 6.

TASK 6

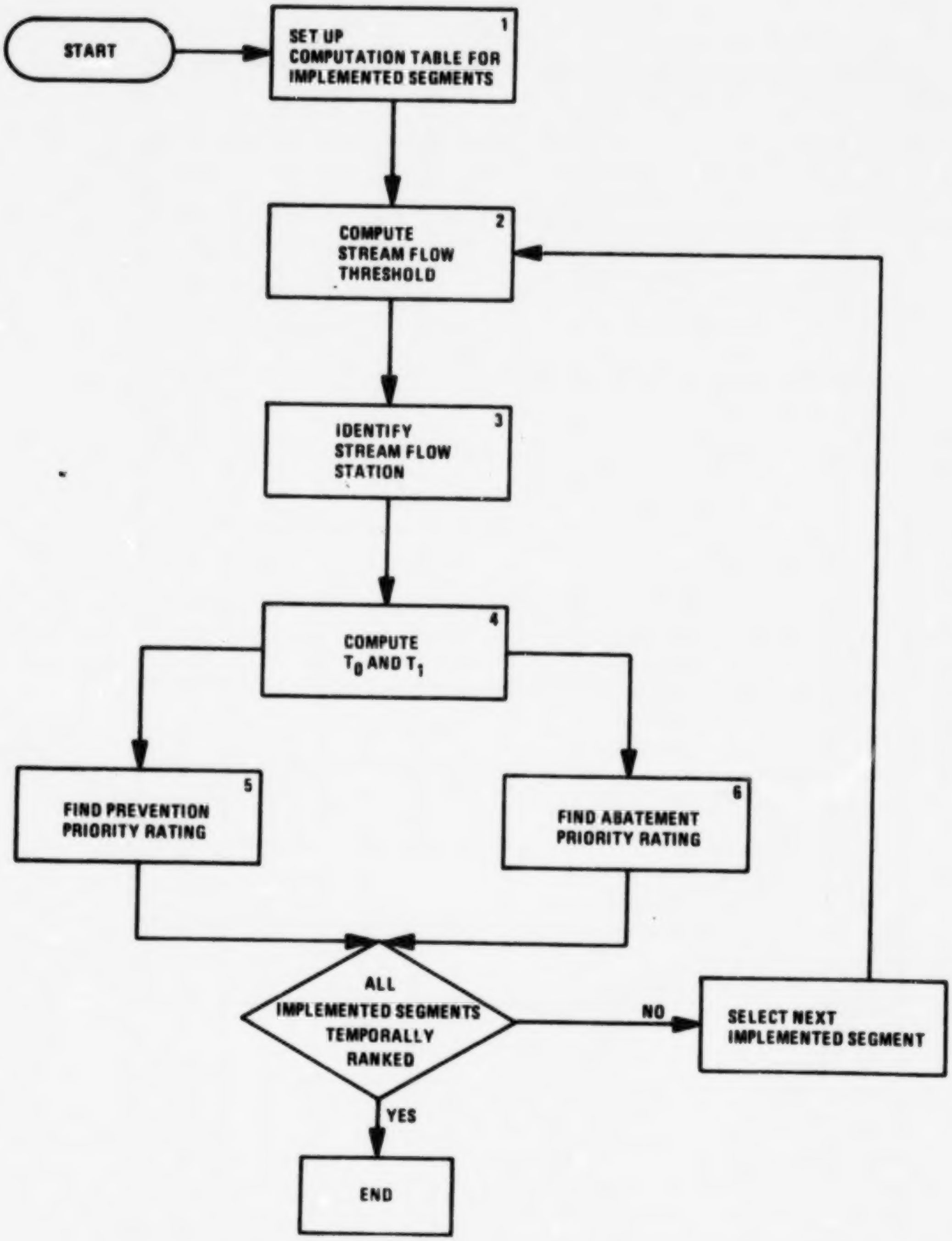
DETERMINATION OF TEMPORAL PRIORITY RATINGS

The actual temporal rating is performed on all segments which are implemented. The ratings are based on two basic sampling objectives— prevention and abatement. All segments in which the probability of violation is very close to zero shall be rated on the basis of the prevention philosophy which is developed in reference [1]. In all segments with a finite probability of violation, the temporal rating shall be based on the abatement philosophy which was developed in this project.

Much of the input information needed for this procedure is developed in the spacial rating procedure. In the Task 6 procedure a computation table, illustrated in Table G-11 for the BOD-DO case, should be filled out sequentially from left to right for each segment which is implemented. The logical flow of this Task is illustrated for a single design parameter flow chart in Figure G-18.

Table G-11. Computation Table for Temporal Priority Rating

N'	N	Q	Q_g	C_{sat}	C_m	C_t	D_{bk}	Q_t		ΔQ	T_0	T_1	Δ	M
Implementation Sequence No.	Segment Number	Stream Flow (l/sec)	Effluent Group Flow (l/sec)	Saturation DO Conc. (mg/l)	Maximum DO Conc. (mg/l)	Threshold DO Conc. (mg/l)	Background DO Deficit (mg/l)	Threshold Stream Flow (CFS)	Stream Flow Station	Stream Flow Adjustments (CFS)	Non-Violation Duation (days)	Violation Duration (days)	Sampling Period (days)	Priority Measure
1														
2														
3														
4														
5														
6														
7														
8														
9														



START
1
SET UP COMPUTATION TABLE FOR IMPLEMENTED SEGMENTS
2
COMPUTE STREAM FLOW THRESHOLD
3
IDENTIFY STREAM FLOW STATION
4
COMPUTE T_0 AND T_1
5
FIND PREVENTION PRIORITY RATING
6
FIND ABATEMENT PRIORITY RATING
ALL IMPLEMENTED SEGMENTS TEMPORALLY RANKED
NO
SELECT NEXT IMPLEMENTED SEGMENT
YES
END

Figure G-18. Logic Flow for Task 6

TASK 6, ACTIVITY 1—SET UP COMPUTATION FOR TEMPORAL PRIORITY RATING

Objective

Enter information pertinent to the temporal rating procedure in the Task 6 Computation Table for implemented segments.

Outputs

- Task 6 Computation Table containing values of $Q(I, N-1)$, $Q_g(N)$, $C_m(I,N)$, $C(I,N)$ and $C_{bk}(I,N)$ for each implemented segment N. (For BOD case, $C_{sat}(N)$ also.)

Inputs

- Computation Table G-8—$Q(N)$, $Q_g(N)$, $C_{sat}(I)$.
- Computation Table G-10—$C_m(I,N)$, $C_T(I,N)$, $C_{bk}(I)$.

Procedure

- For each design parameter, determine which segments are to be implemented and set up a computation table, such as Table G-11 with a row for each segment. (Table G-11, for BOD-DO, is used here as the prototype.)
- In the segment row, N, fill in the information from Tables G-8 and G-10 $C_m(I,N)$, $G(N-1)$, $Q_g(N)$, $C_{sat}(N)$, $C_T(I,N)$, $C_{bk}(I,N)$, corresponding to parameter I.
- Go to Activity 2.

TASK 6, ACTIVITY 2—COMPUTE Q_t FOR EACH SEGMENT

Objective

Compute the stream flow threshold values $Q_t(I,N)$.

Output

- $Q_t(I,N)$ in ft^3/sec.

Inputs

- Computation Table G-11—$C_m(I,N)$, $Q(N)$, $Q_g(N)$, $C_T(I,N)$, $C_{bk}(I,N)$, $C_{sat}(N)$.

Procedure

- Compute $Q_t(I, N)$ for design parameter I:

$$Q_t(I, N) = \frac{C_m(I, N) * \left[Q(N-1) + Q_g(N)\right]}{C_t(I, N)\ C_{bk}(I, N)} - Q_g(N)$$

For DO compute:

$$Q_t(DO, N) = \frac{D_m(N) * \left[Q(N-1) + Q_g(N)\right]}{C_{sat}(DO, N) - C_g(DO, N) - C_{bk}(DO, N)} - Q_g(N)$$

- Convert $Q_t(I, N)$ from 1/sec to ft^3/sec using Table G-1.
- Enter $Q_t(I, N)$ in Computation Table G-11.
- Go to Activity 3.

TASK 6, ACTIVITY 3 — IDENTIFY STREAM FLOW DATA STATION WITH EACH SEGMENT

Objective

Identify the USGS stream gauging station associated with each segment.

Output

- USGS Station Identification and $Q(N)$.

Inputs

- Task 1, Activity 4 — situation map with gauging stations and river miles
- Computation Table G-8 — $Q(N)$
- Computation Table G-10 — $x_m(I, N)$.

Procedure

- Identify the stream flow stations nearest to $x_m(I, N)$ of each segment N.
- Associate the stream flow station which has the average (over the system duration) stream flow closest to that of the segment N, ($Q(N)$).
- Find the difference in average stream flow between the specified segment (N), and the gauging station and call it $\Delta Q(N)$.

- Enter the stream flow station and $\Delta Q(N)$ in Computation Table G-11.
- Go to Activity 4.

TASK 6, ACTIVITY 4—COMPUTE T_0 AND T_1 FOR EACH SEGMENT

Objective

Compute the average number of consecutive days $\left[T_0(I,N)\right]$ the stream flow is above $Q_t(I,N)$, and the average number of consecutive days $\left[T_1(I,N)\right]$ the flow is below $Q_t(I,N)$.

Output

- $T_0(I,N)$, $T_1(I,N)$ in days.

Inputs

- Task 1, Activity 2—Geological Survey "Water Resources Data"
- Computation Table G-11—Q_t, ΔQ.

Procedure

- Extract USGS daily stream flow data for several years over the system duration on the station identified in Task 6, Activity 3.
- Compute the average number of consecutive days $\left[T_0(I,N)\right]$ the stream flow, from the previous step, is above $Q_t + \Delta Q$.
- Compute the average number of consecutive days $\left[T_1(I,N)\right]$ the stream flow is below $Q_t + \Delta Q$.
- Enter $T_0(I,N)$, $T_1(I,N)$ in Computation Table G-11.
- If there are no crossings below $Q_t + \Delta Q$, then go to Activity 5.
- If there are are crossings below $Q_t + \Delta Q$, then go to Activity 6.

TASK 6, ACTIVITY 5—FIND TEMPORAL PRIORITY RATINGS BASED ON PREVENTION OBJECTIVES

Objective

Determine the priority rating of sampling frequencies in segments with very low probability of violation (based on prevention, rather than abatement objectives).

Output

- Effectiveness ratings of sampling frequencies.

Inputs

- Computation Table G-10 — σ (I, N)
- Computation Table G-11 — C_m (I, N)

Procedure

- Perform the following steps iteratively letting W be h$\cdot$(.1), where h represents the hth iteration from 1 to 10.
  - a) Compute the accuracy limit to be allowed in samples for each parameter as a function of the parameter expected $A_1(I) = W \cdot C_m(I, N)$ value: For example, when W = .1, the accuracy must be within 10% of the parameter mean.
  - b) Using the standard deviation from the data station nearest to the segment and over the system duration compute the number of samples needed to give 95% probability that the sample mean is within $A_1(I)$ of the actual mean.

    $$n(I) = \frac{3.84 \cdot [\sigma(I)]^2}{[A_1(I)]^2}$$

  - c) After the two preceding steps have been performed for all parameters compute

    $$n = \frac{1}{v} \sum_{I=1}^{v} n(I)$$

    where v = the number of parameters and n is the number of samples that should be taken over the system duration to satisfy the accuracy limits given by W.

- Construct a table such as the following giving effectiveness vs sampling frequency.

Effectiveness $A_1(I)$	Number of samples per year, n
±10% C(I, N)	25
±20%	7
±30%	4
±40%	3
±50%	2
±60%	1
±70%	1
±90%	1
±100%	1

- **If, for each parameter, the effectiveness rating has been found for all implemented segments, end the procedure; if not, go back to Task 6, Activity 2.**

TASK 6, ACTIVITY 6 — FIND TEMPORAL PRIORITY RATINGS BASED ON ABATEMENT OBJECTIVES

Objectives

Determine the priority rating of sampling frequencies in segments with finite probability of violation (based on abatement objectives).

Output

- **Effectiveness ratings of given sampling frequencies, or sampling frequencies for given effectiveness ratings.**

Inputs

- **Computation Table G-11 — T_0, T_1 and either M or Δ.**

Procedure

- **Using Figure G-19 find the effectiveness M, as a function of T_1, T_0 and the sampling period, Δ(which is 1/frequency). (This figure may also be used for the inverse case: find the sampling period (frequency) for a given effectiveness rating.**
- **Enter M in Computation Table G-11.**
- **If, for each parameter, the effectiveness rating had been found for all implemented segments, end the procedure; if not, go back to Task 6, Activity 2.**

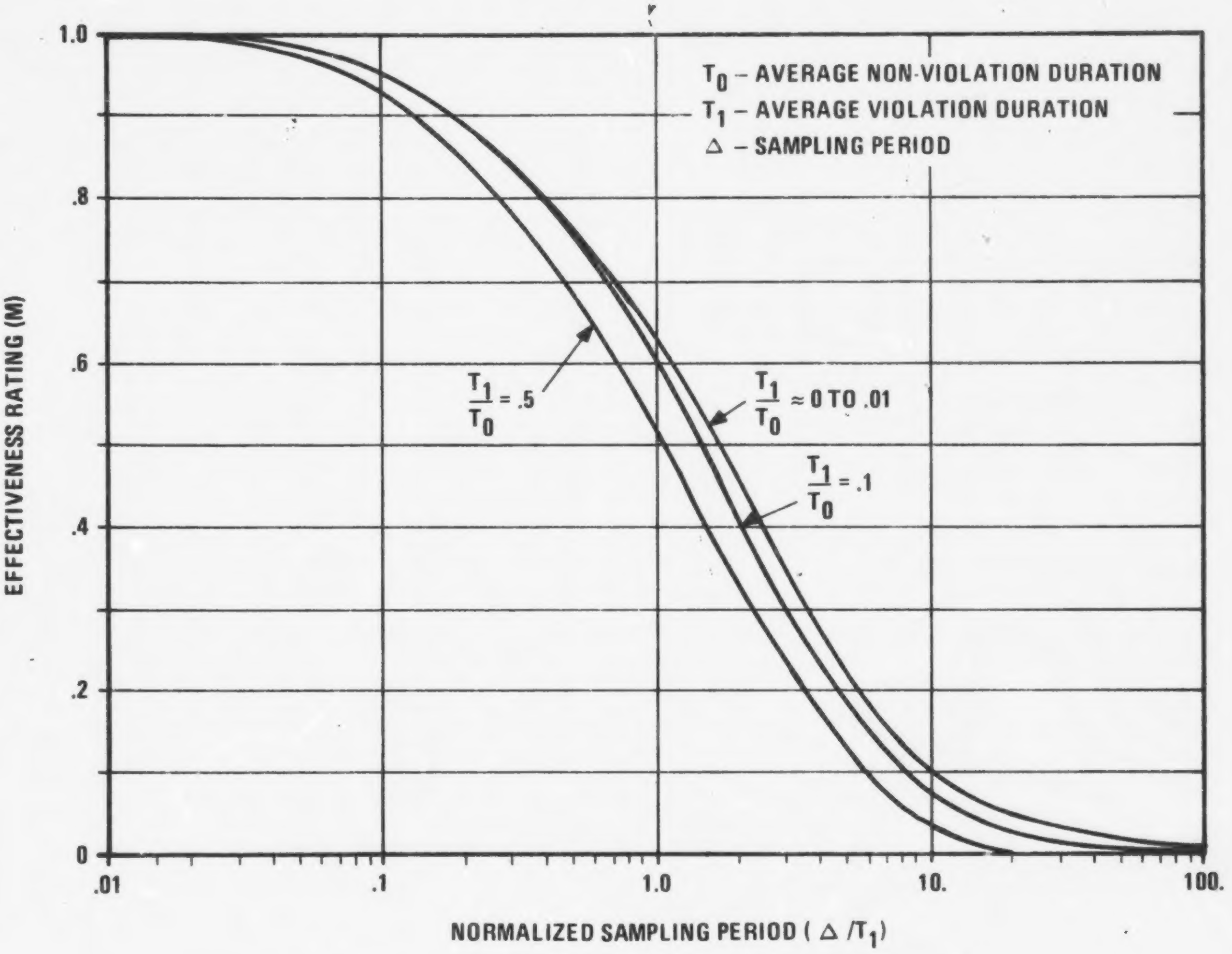


Figure G-19. Temporal Effectiveness Rating as a Function of T_1, T_0 and Δ